

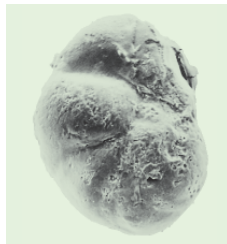
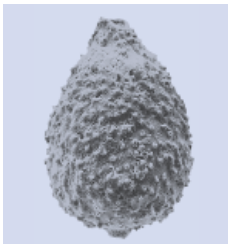
THE FORAMINIFERA OF
THE PORTLANDIAN (LATE
JURASSIC) BETHELSDORP
FORMATION OF THE
ONSHORE ALGOA BASIN,
EASTERN CAPE PROVINCE



THEIR STRATIGRAPHIC POSITION
COMPARED WITH OTHER EARLY
GRABEN INFILL SUCCESSIONS OF
THE SOUTH AFRICAN CONTINENTAL
MARGIN



I.K. McMillan



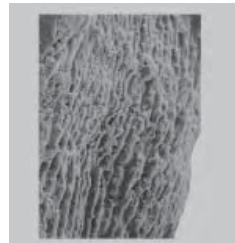
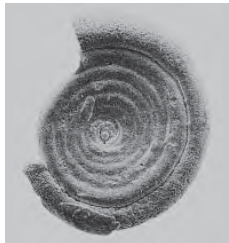
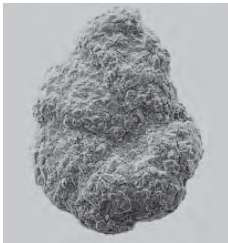
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ABSTRACT

Four borehole sections (BT 1/74, NR 1/15, ST 1/71 and SW 1/08) and three outcrops (Bethelsdorp Salt Pan, Chatty and North End Lake), all sited in the onshore Uitenhage Trough, one of the fault-bounded compartments of the Algoa Basin, all intersect the Bethelsdorp Formation. The Bethelsdorp Formation is regarded as being coeval with the Colchester Formation of the adjacent Sundays River Trough, and with the Vaca Muerta Formation of the Neuquén Basin in Argentina. Three borehole sections and one of the outcrops reveal distinctive benthic foraminifera assemblages that indicate a latest Jurassic (Portlandian) age. The exclusively siliciclastic Bethelsdorp Formation consists of greenish-grey claystones, often with a marked high-gamma character, as well as minor thin sandstones. Dating of the Bethelsdorp Formation helps define the age of the earliest sedimentation in the Algoa Basin. On the basis of differences in the benthic foraminifera assemblages, the Bethelsdorp Formation is regarded as having accumulated in hypersaline mud-flat, hyposaline estuarine channel, and normal marine inner neritic environments. The Bethelsdorp succession shows slight shallowing upwards, and is also distinguished by eight peaks in foraminiferal abundance, that correlate between boreholes. The locally diverse benthic foraminifera assemblages are entirely unlike those of the Late Valanginian to Hauterivian Sundays River Formation. The assemblages are also unlike clearly coeval ones from the Bethelsdorp Formation equivalents in the offshore Pletmos (such as in borehole PB-A1), Gamtoos (as in borehole Ha-H1), and Algoa Basins (as in Hb-A1 in the Port Elizabeth Trough or Hb-D1 in the offshore Uitenhage Trough). Bethelsdorp Formation foraminifera assemblages are evidently strongly facies controlled, and also show little similarity with those published up to now from the Vaca Muerta Formation of the Neuquén Basin. The foraminiferal assemblages from the Bethelsdorp Formation consist of 93 species or species groups, of which six species are described as new. Also present are bryozoans, solitary corals, calcareous alga segments, calcareous worm tubes and serpulids, scaphopods, arthropod claws and skeletal fragments, marine and non-marine ostracods (*Cypridea*-dominated assemblages), gastropods, bivalves (including oysters and *Inoceramus* prisms), holothurian sclerites, crinoid ossicles, ophiuroid ossicles, echinoid spines, plates and pedicellaria, indeterminate echinoderm skeletal elements, fish bone, teeth, scales and otoliths, fossil wood, charophyte oogonia and megasporos.

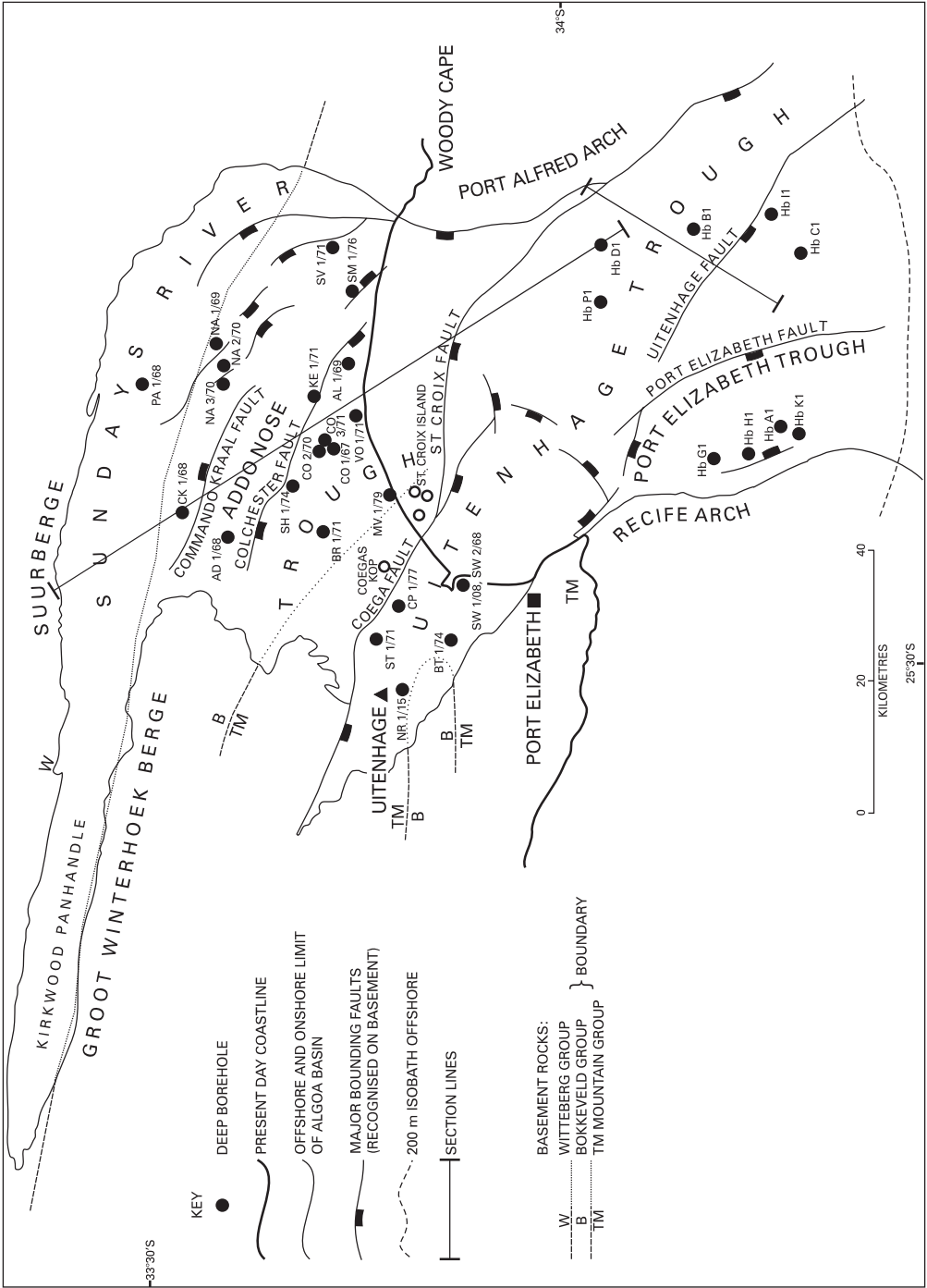


FIGURE 1
Outline, structure and sites of deep boreholes of the onshore and offshore Algoa Basin, Eastern Cape Province, South Africa

INTRODUCTION

The onshore part of the elongate Uitenhage Trough, a simple half-graben, is located in the southwestern part of the onshore Algoa Basin, and extends inland across the Nelson Mandela Metropole from the city of Port Elizabeth to just past the town of Uitenhage (Fig. 1). The trough is bounded on its north-eastern margin by the Coega Fault, and the Late Jurassic-Early Cretaceous sedimentary basin infill thins steadily to the south-west, away from the bounding fault. The Coega Fault extends offshore and links with the St Croix Fault system (Doherty, 1993), so that the Uitenhage Trough extends obliquely across the Algoa Basin, irregularly deepening towards its offshore south-eastern corner. The maximum width of the Uitenhage Trough is about 30km, and altogether it is about 140km long. Four deep boreholes have been drilled in the onshore portion of the Uitenhage Trough (SW 1/08, NR 1/15; ST 1/71 and BT 1/74), and five have been drilled in the offshore portion (Hb-C1 in 1978, Hb-D1 in 1984, and Hb-I1, Hb-B1 and Hb-P1 all in 1987).

This study concentrates on the foraminifera of the marine-influenced Bethelsdorp Formation (formerly regarded as part of the Colchester Shale Member), and their biostratigraphic significance, from three of the four onshore boreholes and one of the three outcrops. This study follows on from analysis of the foraminifera of the Late Valanginian to Hauterivian Sundays River Formation (McMillan, 2003a), and of the overlying Pliocene–Pleistocene Upper Algoa Group (McMillan, 1990). The deep geology of the onshore and offshore Uitenhage Trough is detailed by Rigassi & Dixon (1972), Winter (1972, 1973, 1979), McLachlan & McMillan (1976), Malan *et al.* (1990), Bate & Malan (1992), Malan (1993), Broad & Mills (1993), McMillan *et al.* (1997), Singh (2000), McMillan (2003b) and Singh *et al.* (2005).

The overwhelming majority of benthic foraminifera species detailed from the Bethelsdorp and Sundays River formations (McMillan, 2003a; this volume) are characterised by smooth-walled, unornamented tests. In contrast the majority of species from the Jurassic and early Cretaceous of the Mahajanga Basin, north-west Madagascar (Espitalié & Sigal, 1963b) are strongly ornamented with ribs, reticulations, tubercles, and so on. If this difference is real does it imply, for example, a biotic response to sea-floor energy levels caused by currents and swell?

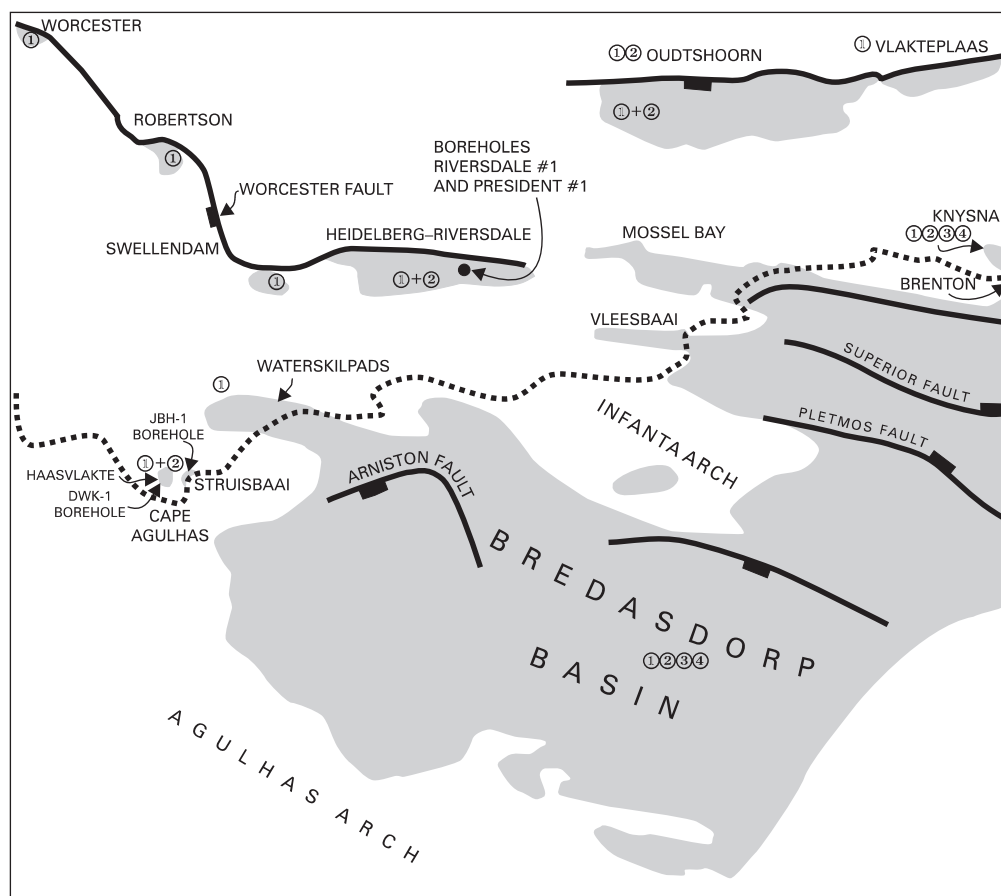
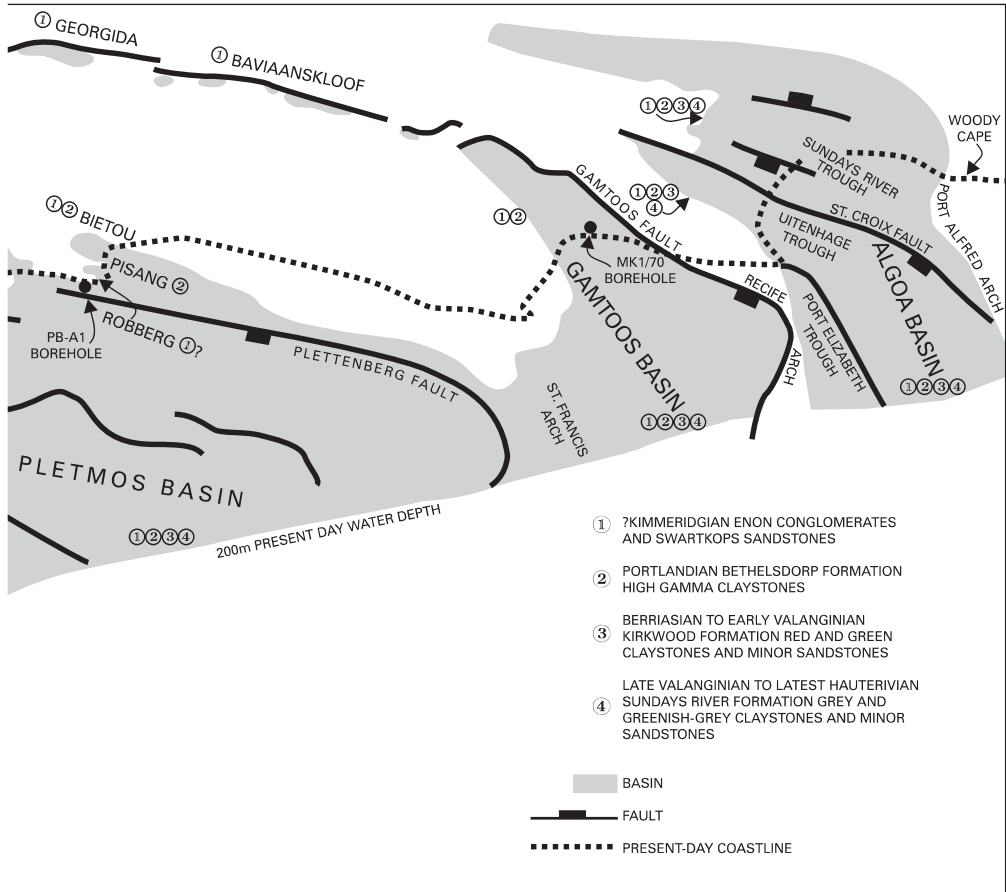


FIGURE 2

Distribution onshore and offshore of Kimmeridgian to Hauterivian graben fills, southern coast of South Africa

Analysis of Basin Compartment Histories

Even a cursory examination of the areal distributions of the long-defined rock units of the onshore Algoa Basin shows them to be strongly localised. For example, in the north-western margin of the basin the Enon conglomerates are in places at least 300m thick, whereas along the north-eastern margin there is hardly a record of Enon conglomerate. Overlying the coarse-siliciclastic units of the Enon conglomerates and Swartkops sandstones, there are the clearly coarse-clastic-starved, organic-rich, high-gamma claystones of the Colchester and Bethelsdorp Formations. Why should this be so? Why are the facies boundaries of the fluvial sediment units of the Kirkwood Formation and the inner neritic sediment units of the Infanta Formation both obliquely stacked, so that these facies advance seawards and shallow upwards; whereas the neritic sediment units of the Sundays River Formation are vertically stacked, and show no trace of shallowing upward?



It is evident that these localised distributions of different sediment types reflect the availability of accommodation space caused by often extremely localised basin subsidence during any given time period across the length and breadth of the basin. Basin subsidence was driven by episodic movement on the major bounding faults, as a response to the pull-apart tectonic regime incurred as the continent of Gondwana disintegrated. These sediment distributions tell us accurately when and where the basin was subsiding during its roughly 27 million year long history, and portray for us the full consequential complexity of repeated changes of sediment style during the period. These concepts stem from the pioneering work of Barrell (1917), Du Toit (1922) and later early 20th century authors, summarised by Miall (2004), and rediscovered yet again by McMillan (2003b).

Introduction: Sundays River Trough

The early sedimentation and subsidence histories of the mostly onshore Sundays River Trough, and the mainly offshore Uitenhage Trough, both down-faulted compartments of the proximal part of the Kimmeridgian to Hauterivian-aged Algoa Basin, are distinctly different. In the Sundays River Trough (McLachlan &

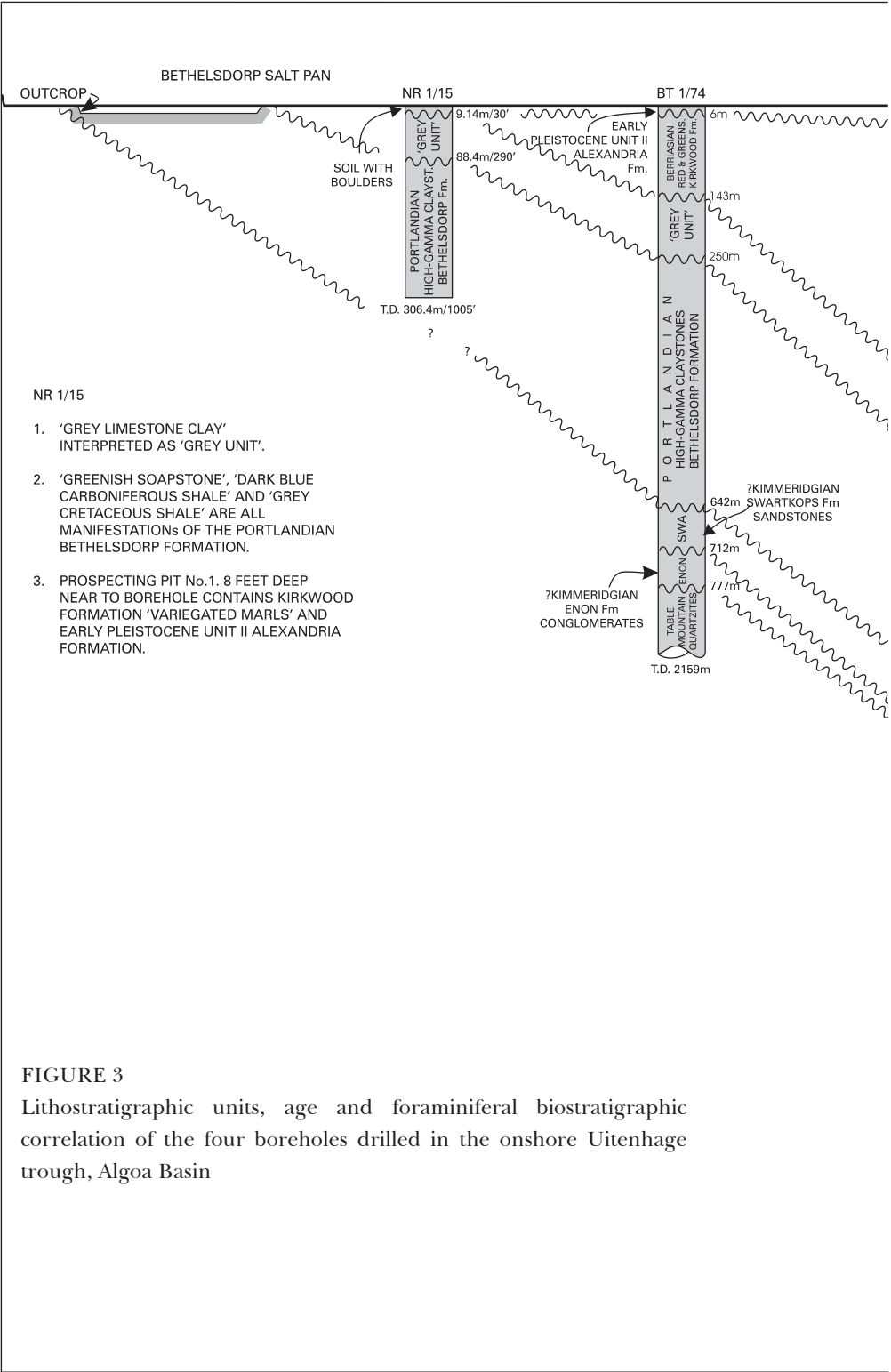
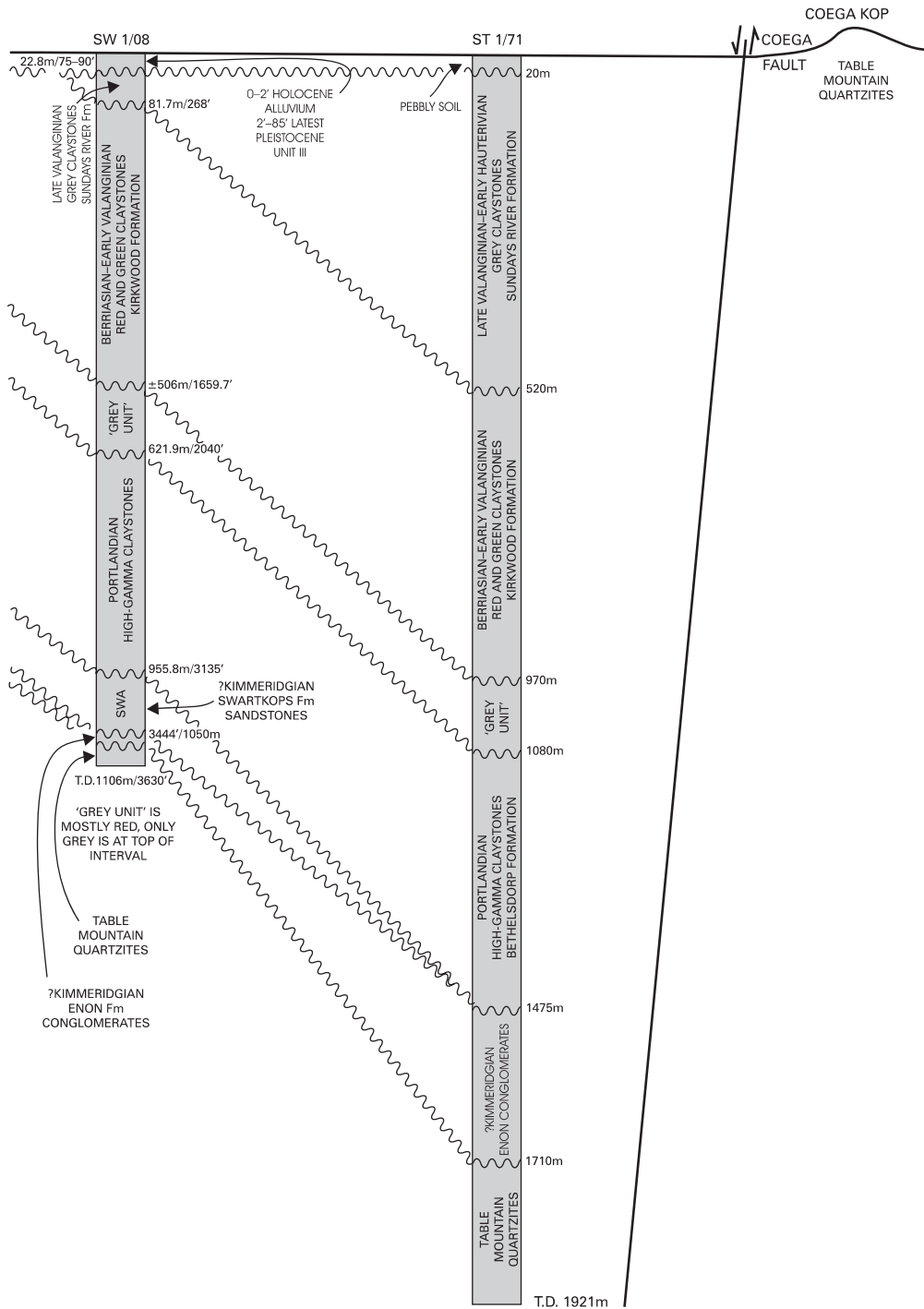
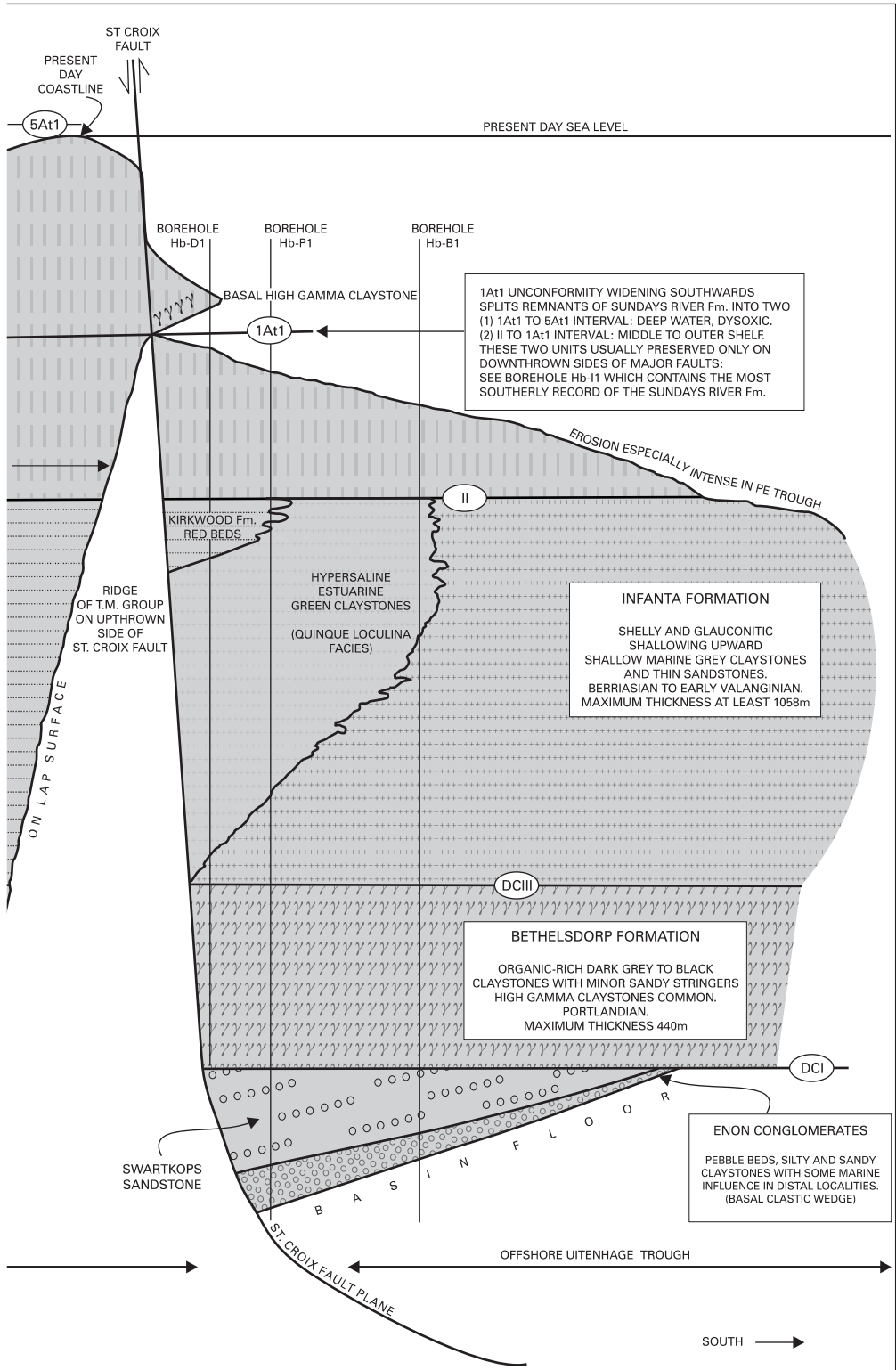


FIGURE 3
Lithostratigraphic units, age and foraminiferal biostratigraphic correlation of the four boreholes drilled in the onshore Uitenhage trough, Algoa Basin





| | | | |
|--|--|--|--|
| OPERATOR SOEKOR (PTY) LTD. | OPERATOR SOEKOR (PTY) LTD. | OPERATOR ALGOA OIL COMPANY LTD. | OPERATOR UITENHAGE PETROLEUM AND MINING CO. |
| HOLE BT 1/74 ROTARY- CUTTINGS | HOLE ST 1/71 ROTARY- CUTTINGS | HOLE SW 1/08 JUMPER DRILL | HOLE NR 1/15 PERCUSSION DRILL |
| FARM BETHELSDORP COMMONAGE | FARM SALT PAN | FARM SWARTKOPS | FARM NAROES |
| CO-ORDINATES 25°32'00"E/33°51'08"S | CO-ORDINATES 25°32'00"E/33°46'30"S | CO-ORDINATES 25°36'38"E/33°52'47"S | CO-ORDINATES 25°3833'E/33°81667'S |
| 0-6 m: LATEST QUATERNARY | SOIL 0-20 m: LATEST QUATERNARY | 0-90'/27.4 m: LATEST QUATERNARY | 0-30'/0-9.14 m: SUBSOIL + BOULDERS QUATERNARY |
| 6-143 m: KIRKWOOD FORMATION | 20-520 m: SUNDAY RIVER FORMATION | 90-280'/85.4 m: SUNDAYS RIVER FORMATION | 30-290'/9.14-88.4 m: "GREY UNIT" |
| 143-250 m: "GREY UNIT" | 520-970 m: KIRKWOOD FORMATION | 280-1659.7'/506 m: KIRKWOOD FORMATION | 290-1005'/88.4-306.4 m (TOTAL DEPTH): BETHELSDORP FORMATION |
| 250-642 m: BETHELSDORP FORMATION | 970-1080 m: "GREY UNIT" | 1659.7-2040'/622 m: "GREY UNIT" | |
| 642-712 m: SWARTKOPS FORMATION | 1080-1475 m: BETHELSDORP FORMATION | 2040-3135'/956 m: BETHELSDORP FORMATION | |
| 712-777 m: ENON FORMATION | 1475-1718 m: ENON FORMATION | 3135-3453.8'/1053 m: SWARTKOPS FORMATION | |
| TABLE MOUNTAIN QUARTZITES | TABLE MOUNTAIN QUARTZITES | 3453.8-3491.8'/1064.6 m: ENON CONGLOMERATE FORMATION | |
| | *NO SWARTKOPS SANDSTONES IN THIS BOREHOLE | TABLE MOUNTAIN QUARTZITES | *NOTE THAT BASAL KIRKWOOD FORMATION "VARIEGATED CLAYSTONES" FOUND IN PIT NEAR TO WELL SITE |

TABLE 1
Co-ordinates and basic stratigraphic units for the four deep boreholes of the onshore Uitenhage Trough. All depths given are below Kelly Bushing.

McMillan, 1976, and references therein; McMillan, 2003a, and references therein) the stratigraphic succession (from bottom to top) consists of variable and localised thicknesses of essentially unfossiliferous fluvial conglomerates (Enon Formation,

up to 200m thick in borehole AL 1/69 and up to 300m in outcrop (Rigassi, 1968)). Locally these are overlain by fluvial unfossiliferous sandstones of the Swartkops Formation – up to 95m in VO 1/71. These conglomerates and sandstones are unconformably overlain in the central trough by localised lacustrine interbedded brown, black, red and green claystones, often rich in organic debris and characterised by a high-gamma response (Colchester Formation, up to about 160m thick in borehole AL 1/69). The lacustrine Colchester Formation appears to be limited to that part of the Sundays River Trough lying to the south of the Colchester Fault (McMillan, 2003a, Fig. 2). Non-marine ostracods (mainly *Cypridea* and *Theriosynoecum*, according to unpublished studies by P.W. Brenner and V.H. Valicenti) and charophyte oogonia occur widely in the Colchester Formation, but there are no *in situ* marine microfossils or macrofossils. The Enon and Colchester formations are both unconformably overlain by fluvial red and green claystones and minor sandstones of the Kirkwood Formation (up to about 2050m thick in borehole AL 1/69). The Kirkwood Formation is overlain by ?fluvial to innermost neritic to uppermost bathyal grey claystones and minor sandstones (Sundays River Formation, up to 1745m thick in borehole AL 1/69). The Sundays River Formation appears to be conformable with the underlying Kirkwood Formation in the Sundays River Trough, but in the offshore Algoa Basin (for example in borehole Hb-D1), and also in the offshore Gamtoos and Pletmos Basins, this boundary is clearly unconformable, where it is marked by seismic horizons II (Algoa) and J1 (Gamtoos) and their equivalents. The complete Kimmeridgian to Hauterivian succession in the Sundays River Trough attains a maximum thickness of 4160m in onshore borehole AL 1/69. Significantly, Shone (1978) noted the presence of an unconformity along the northern margin of the Sundays River Trough between the underlying Enon conglomerates and the overlying Kirkwood red and green claystones with sandstones, on the basis of differences in palaeoslope between the two units. Recognition of this major sequence boundary is crucial to an understanding of the early basin history and sedimentation pattern preserved in the southern Cape Late Jurassic–Early Cretaceous basins, and it is discussed in detail in the initial part of this article.

Introduction: Uitenhage Trough

In contrast, the proximal Uitenhage Trough is distinguished by variable thicknesses (up to 243m in borehole ST 1/71) of localised Enon conglomerates, unconformably overlain by a thin localised unit (up to 92m in borehole SW 1/08) of fluvial sandstones (Swartkops Formation). This in turn is unconformably overlain by a thick succession (392m in borehole BT 1/74) of mud-flat to estuarine to inner neritic green-grey, often organic rich, claystones (often with high-gamma characteristics), and minor sandstones, with foraminifera, marine and non-marine ostracods, and charophyte oogonia, herein termed the Bethelsdorp Formation. The unconformably overlying fluvial red and green claystones of the Kirkwood Formation are distinctly thinner throughout the Uitenhage Trough (560m in

borehole ST 1/71) than in the Sundays River Trough, but they are followed in turn by the probably conformably overlying marine grey claystones of the Sundays River Formation. Both the latter two formations are lithologically similar to those of the Sundays River Trough. Maximum thickness (1700m) of the Kimmeridgian to Hauterivian succession in the onshore Uitenhage Trough was encountered in borehole ST 1/71, but in the offshore Uitenhage Trough the graben-fill succession is locally at least 3100m thick (borehole Hb-D1) in major depocentres. Further offshore, in the southernmost Algoa, Gamtoos and Pletmos Basins, almost the entire Kimmeridgian to Hauterivian succession accumulated in a fully normal marine environment.

Stratigraphic Overview of Southern Cape Graben Fills

As a result of foraminifera and ostracod biostratigraphic analysis of the borehole sections drilled in the offshore Algoa, Gamtoos and Pletmos Basins, coupled with a critical analysis of available seismic sections, it is now possible to understand the sequence stratigraphic history of the Algoa Basin in a much clearer light. This has resulted in, firstly, the abandonment of the Atherstone-initiated facies model, dating from 1857, and elaborated by Rogers & Schwarz (1901) and McLachlan & McMillan (1976), in which the Enon conglomerates, the Kirkwood fluvial claystones and the Sundays River marine claystones were seen as diachronous facies of the same rock succession. Secondly, based on foraminifera and ostracod biostratigraphy from distal borehole intersections (see Time-Equivalent Sections, below), and also comparison with the stratigraphic succession of the Neuquén Basin of Argentina, the Algoa succession can now be attributed the following discrete ages: Enon Formation (microfossils only in extremely distal settings, probably Kimmeridgian); Swartkops Formation (no microfossils, but probably late Kimmeridgian); Colchester Formation and Bethelsdorp Formation (Portlandian); Kirkwood Formation (scarcely any microfossils except pollens and spores, but probably Berriasian to Early Valanginian); Sundays River Formation (Late Valanginian to latest Hauterivian). Essentially, each one of these units is unconformably bounded, or at least locally so, from its neighbours. The Enon and Swartkops Formation constitute the Basal Clastic Wedge, evident as a discrete initial sedimentary package in the Algoa basin infill succession.

The Suurberg Group volcanics that lie around the northern periphery of the Sundays River Trough have long been suspected to correlate with the Jurassic Stormberg volcanics (Rogers *et al.*, 1929, p. 143), and this has been confirmed by isotopic signatures (Marsh *et al.*, 1979). These volcanics have provided a single radiometric age of 162 Ma. ± 7 (McLachlan & McMillan, 1976, p. 198). Marsh *et al.* (1979) have regarded this single date as unreliable, as they believed that all material available at the sampled outcrop site is weathered. However, if this single date is valid, the Suurberg Group thus must unconformably underlie the oldest sedimentary infill (Enon conglomerates, probably Kimmeridgian, about 150 Ma.

at oldest) of the Algoa Basin with a substantial time gap of up to 12 Ma. Hill (1975) reported that the Enon Formation overlies the Suurberg Group apparently conformably, but previously Rogers *et al.* (1929, p.143) had regarded this as an unconformable boundary. The Suurberg Group has not been intersected in any of the deep hydrocarbon exploration boreholes drilled up to now in the Algoa Basin. It is not clear whether the Suurberg Group accumulated prior to, or after, initiation of subsidence of the Algoa Basin half-graben structures.

It is intriguing to speculate on whether the emplacement of the large impact crater at Morokweng in north-western South Africa (Koeberl *et al.*, 1997; Reimold *et al.*, 2002, and references therein), dated at about 145 Ma at the Jurassic-Cretaceous boundary, played any influential part in affecting sedimentation in the Algoa Basin (and the other rift basins too) at the Bethelsdorp/Colchester–Kirkwood boundary. At present, this lithostratigraphic boundary is the only potential candidate for the southern African Jurassic–Cretaceous boundary. The Mjølner impact crater, located in the western Barents Sea, north of Norway (Smelror & Dypvik, 2005, and references therein), is of comparable age (142.2 ± 2.6 Ma).

TIME-EQUIVALENT SUCCESSIONS

Foraminiferal biozones and other datums recognised up to the present in the lower part of the graben fill successions (Kimmeridgian to Early Valanginian, or pre-Sundays River Formation) of the Bredasdorp, Pletmos, Gamtoos and Algoa Basins, are shown in Fig. 18.

Port Elizabeth Trough, offshore Algoa Basin

The seismic pattern of the Port Elizabeth Trough is displayed in a foraminiferally dated dip line running south-west to north-east across the trough (McMillan *et al.*, 1997, Fig. 19; and see Fig. 11 pages 34–35). Up to now, four boreholes have been drilled in the Port Elizabeth Trough, two of which intersect an incomplete early graben fill succession (boreholes Hb-A1 and Hb-K1), and two which intersect only an even more attenuated Berriasian–Early Valanginian succession (Hb-G1, Hb-H1). Post-sedimentary uplift and erosion of the graben fill succession has been particularly intense here, for none of the four holes has any Late Valanginian to latest Hauterivian succession (Horizon II to 1At1 to 5At1 intervals) preserved. Both Hb-A1 and Hb-K1 intersected the Kimmeridgian basal clastic wedge, and this is 271m thick in the former hole. Apart from the basal clastic wedge, which here accumulated mostly in a fluvial regime, with minor marine influence, the entire overlying Portlandian to Early Valanginian succession accumulated in from uppermost bathyal environments at the base, shallowing up to innermost neritic environments at the top of the succession. Seismic horizon DCIII marks the top of the Portlandian Bethelsdorp Formation equivalent. This Portlandian unit consists of up to 370m of locally high-gamma and organic-rich black claystones with a diverse foraminifera assemblage. Typical benthic foraminifera include frequently abundant ornate *Reinholdella* cf. *R. valendisensis* (Bartenstein & Brand), *Astacolus microdictyotos* Espitalié & Sigal Group 2, *Epistomina* cf. *E. mosquensis* Uhlig, and there are a number of species indicative of a latest Jurassic age. This foraminiferal assemblage, with its predominance of aragonitic-walled species (*Reinholdella* and *Epistomina*), is quite unlike that of the Portlandian in the onshore Uitenhage Trough, described herein, or those of the coeval units in the offshore Uitenhage Trough, the Gamtoos or the Pletmos Basins. The assemblage suggests an outermost neritic or uppermost bathyal (shelf-break) siliciclastic-starved and rather dysoxic depositional environment, reflecting the organic-rich milieu.

The distinctive benthic zone foraminifera, fat *Lagena* sp., used to mark the top of the Early Valanginian succession (McMillan *et al.*, 1997, Fig. 3), and which is part of the pre-Sundays River Formation foraminiferal assemblage and referable to the Infanta Formation (base Berriasian to top Early Valanginian in age), appears 45m below the 1At1 unconformity in borehole Hb-G1. This mid Valanginian age is the stratigraphically highest in the graben fill of all the four boreholes drilled in the Port Elizabeth Trough. However, because of the widespread occurrence of shallow marine, often littoral, innermost neritic facies, in which thin glauconitic sandstones and thin shelly clays are widespread, and foraminiferal assemblages are often poor, it is often not clear if single records of fat *Lagena* sp., *Planularia tricarlinella* and other age-diagnostic benthic foraminifera truly reflect the highest stratigraphic occurrences of these species. This problem of true stratigraphic ranges besets studies of the Infanta Formation especially in the southernmost offshore Pletmos, Gamtoos and Algoa Basins, and on occasion has led to major discrepancies between seismically-derived and foraminiferally-derived ages.

Uitenhage Trough, offshore Algoa Basin

The seismic character of the offshore Uitenhage Trough is displayed in a south-west to north-east aligned dip-line (McMillan *et al.*, 1997, Fig. 20, reproduced here with amendments as Fig. 11), dated from foraminiferal studies. This seismic section shows the often-complex bed relationships of this trough, as well as the magnitude of the St Croix Fault system, which underlies almost half of the offshore part of the trough (Doherty, 1993). Since five boreholes have been drilled in the offshore Uitenhage Trough, this extensive half-graben remains only partly explored, and the nature of the most distal stratigraphic succession is as yet unknown. All five boreholes drilled up to now have intersected similar stratigraphic successions, but displaying very different thicknesses. Boreholes Hb-P1 (at least 492m thick) and Hb-B1 (at least 1194m thick) intersected the thickest basal clastic wedge successions (Enon–Kimmeridgian), which here contain interlayered red and grey claystones and red pebble beds and sandstones, together with thicknesses of lower conglomerate, and both successions appear to be entirely non-marine.

Four of the five boreholes intersected a high-gamma marine claystone interval (Bethelsdorp equivalent, Portlandian), 440m thick in borehole Hb-B1, 331m thick in borehole Hb-P1, and 288m in Hb-C1. The interval is also seen in borehole Hb-D1 but is here severely attenuated by the St Croix fault-plane. The more proximal boreholes Hb-D1 and Hb-P1 both intersected an interval of Kirkwood Formation red claystones and green hypersaline estuarine claystones with *Quinqueloculina grisbrooki* n. sp., but the equivalent interval in the more offshore borehole section of Hb-B1 is missing through uplift and erosion. The red claystones in Hb-D1 and Hb-P1 are coeval with the stratigraphically highest part of the onshore Kirkwood Formation. Again, as with the Port Elizabeth Trough, there has been intense planation on the 5At1 (Hauterivian–Barremian boundary) unconformity surface,

especially in the south-eastern part of the offshore Uitenhage Trough, with the result that it is only the more northerly sited offshore boreholes (Hb-D1 and Hb-P1) and holes close to bounding faults (Hb-I1), that intersect equivalent beds to the Sundays River Formation, as understood onshore (see McMillan, 2003a, Fig. 2). The highest foraminiferal biostratigraphic zone identified in the offshore Uitenhage Trough in borehole Hb-D1 is earliest Hauterivian (about 2At1), whereas in the more southerly borehole Hb-B1, sited on an upthrown block, it is topmost Berriasian (large *Haplophragmoides* spp.). The borehole Hb-I1 section is the most complete of all, with beds up to later Hauterivian (3At1 or 4At1), yet also almost the most southerly, as it is sited very close to the downthrown side of the Uitenhage Fault.

Foraminifera assemblages of the Bethelsdorp Formation equivalent (DCI to DCIII interval) in the offshore Uitenhage Trough are generally inner to middle neritic, near-normal marine *Ammobaculites*-, *Haplophragmoides*-, *Lenticulina*- and *Astacolus*-dominated assemblages, not too similar to those of the onshore Uitenhage Trough, but reflecting a markedly more marine environment, and lacking any species typical of estuarine environments. They also lack the outer neritic or upper bathyal foraminifera species, especially the aragonitic *Reinholdella* and *Epistomina* species, which are prevalent in the coeval interval in the Port Elizabeth Trough.

Distal of the Kirkwood Formation red claystones in boreholes Hb-D1 and Hb-P1, there are green claystones which accumulated in hypersaline mudflat settings, as indicated by the monospecific assemblage of the miliolid *Quinqueloculina grisbrooki* n. sp. (see McMillan, 2003a, Figs. 21–24).

Foraminifera assemblages from the offshore equivalent of the Sundays River Formation in boreholes Hb-D1 and Hb-P1 are diverse, similar to those of distal onshore boreholes such as AL 1/69. Only the basal beds are represented in both holes. Firstly there is an attenuated Late Valanginian succession (horizons II to 1At1) of foraminifera biozones C and lower B (McMillan, 2003a), in an outermost shelf or uppermost slope depositional environment. Secondly overlying this is an attenuated 1At1 to probable 2At1 succession with dysoxic character, in an upper slope setting. Because of the dysoxic character in this unit foraminifera assemblages are severely impoverished. Thickness of the two units in Hb-D1 is only 380m, which contrasts profoundly with the 1745m of Sundays River Formation in AL 1/69.

Pletmos Basin

There are several time-equivalent successions of the Enon, Bethelsdorp and Colchester Formations exposed along the South African coast, particularly on the Robberg Peninsula adjacent to Plettenberg Bay, and also at Cape St Blaize near Mossel Bay, both of which constitute proximal portions of the Pletmos Basin graben fill succession, sited on upthrown horsts. From hard, partly cemented

black shale beds, interbedded with the silicified fluvial and littoral sandstones and conglomerates of the Robberg Formation, exposed in the cliffs just west of the Robberg Peninsula, samples collected by I.R. McLachlan in the 1970s yielded agglutinated benthic foraminifera in small numbers, of the genera *Ammobaculites* and *Haplophragmoides*. These foraminifera provide no useful age control for the outcrop, but do indicate that environmental conditions at the time of deposition were innermost neritic and probably slightly hyposaline; that is, there is a fluvial influence. The cemented nature of these rocks suggests the possibility that if there were ever any calcareous benthic foraminifera in the black shales, then they have been destroyed by subsequent calcite leaching and reprecipitation. The occurrence of the black shales within the silicified conglomerate succession of the Robberg Formation suggests their age must be Kimmeridgian, by analogy with the age of the Enon conglomerates. The sedimentary facies and lithostratigraphy of the Robberg Formation have been detailed by Reddering (2000, 2003).

A more complete graben fill succession in the proximal Pletmos Basin was intersected in borehole PB-A1, drilled offshore just south-west of the Robberg Peninsula at 34°09'39.9"S, 23°20'12.13"E. PB-A1 passed through equivalents of the Enon/Robberg conglomerate (145m thick), Bethelsdorp grey claystones (492m thick), Kirkwood red claystones (396m thick) and Sundays River grey claystones (a little more than 539m thick). Unconformably overlying the graben fill is a latest Pleistocene (Eemian–Weichselian sea-level fall, forced regressive systems tract) littoral shelly sand veneer distinguished by *Elphidium crispum* (Linné), in turn unconformably overlain by the Holocene mud belt. McLachlan *et al.* (1976a) described and illustrated the foraminifera and ostracods of the Bethelsdorp equivalent succession in PB-A1 borehole, but the foraminifera in particular became rather confused with those of the overlying Sundays River Formation equivalent because of considerable cavings problems in the borehole. Later unpublished work on the foraminifera of the Bethelsdorp equivalent in PB-A1 shows the assemblage is distinct, quite unlike that of the Sundays River equivalent, and is generally dominated by a few *Astacolus* and *Lenticulina* species occurring in large numbers (McLachlan *et al.*, 1976a, fig. 12, nos 2 and 4). Following McLachlan *et al.* (1976a) and later sample reprocessing, the assemblage consists of the following *in situ* species: *Haplophragmoides* sp. A (occurring partly also in the basal Kirkwood equivalent), *Dorothia subtrochus* (Bartenstein), *Astacolus* sp. A (part), *Epistomina parastelligera* (Hofker) (formerly identified as *Epistomina caracolla* (Roemer)), *Vinelloidea buchenroderi* McMillan and *Vaginulinopsis* gr. *prima* (d'Orbigny). The depositional environment is interpreted as being near to shore, and wave-dominated.

This exact foraminifera assemblage has not been found elsewhere in coeval rock units in Pletmos Basin boreholes. Apart from borehole PB-A1, all other boreholes drilled in the northern part of the Pletmos Basin failed to reach down to the same stratigraphic level, because of the excessive thicknesses of graben-fill succession in

the Plettenberg Graben. Further south, around the Superior High, the Ga-A and Ga-Q boreholes intersected coeval rather sandy grey claystones, reflecting littoral or innermost shelf environments, with limited foraminifera assemblages dominated by smooth-walled *Lenticulina* species. Similar smooth-walled *Lenticulina*-dominated assemblages with few *Epistomina*, and rare ornamented *Epistomina* cf. *E. mosquensis* Uhlig occur in the less sandy grey claystones intersected in boreholes Ga-B1, Gb-J1 and Gb-Gemsbok 1 (the last-named unfortunately mostly turbine drilled across the relevant interval, with the result that claystones were partially melted by the heat, and nearly all of the foraminifera destroyed). From the wider diversity of foraminifera in the vicinity of boreholes Ga-B1, Gb-J1 and Gb-Gemsbok 1, this part of the Pletmos Basin must have been the deepest-water and the most nearly marine (but still only inner neritic) during accumulation of the Portlandian Bethelsdorp Formation equivalent.

In the Pletmos Basin, seismic horizon O marks the top of the Kimmeridgian basal clastic wedge (top Enon/Robberg), seismic horizon B probably marks the top of the Portlandian Bethelsdorp equivalent, and seismic horizon BCI (locally also possibly the higher horizon J) marks the mid Valanginian Kirkwood–Sundays River equivalent boundary. Below horizon B foraminifera assemblages are usually much more diverse than above, and *Lenticulina* and *Epistomina*-dominated assemblages occur. Horizon BCI approximately equates to the first downhole appearance of the informal foraminifera zone species *Lagena* sp. (McMillan *et al.*, 1997, Fig. 3), which marks the first downhole appearance of Early Valanginian pre-Sundays River Formation foraminifera assemblages. Both in borehole PB-A1 and in quite a number of other Plettenberg Graben boreholes in the northern part of the basin (such as Gb-H1, Gb-C1), where Valanginian benthic foraminifera assemblages are much more than usually diverse, horizon 1At1 (formerly horizon C) lies in the latest Valanginian succession, and marks a major unconformity in the topmost part of the *Lenticulina coegaensis* Biozone B (McMillan *et al.*, 1997, Fig. 3; McMillan, 2003a, Fig. 8).

The two onshore extensions of the Pletmos Basin at Plettenberg Bay, designated the Bietou and Pisang Basins, both have a recorded history of grey claystones (Schwarz (1900), Rigassi (1970), McLachlan & McMillan (1976)), and are not far distant from the PB-A1 borehole site, but they have yielded no fossil assemblages of note: they deserve intensive re-examination. Rossouw (1933) provides additional details of the Robberg Peninsula, which has been comprehensively reviewed by Reddering (2000, 2003).

Gamtoos Basin

The Gamtoos Basin onshore borehole MK 1/70 bottomed in a considerable thickness (at least 2150m) of presumably Kimmeridgian Enon conglomerates, overlain by 820m of fluvial to rarely hyposaline marine reddish and greenish-grey

claystones and thin sandstones. Rogers (1906), Winter (1973), and, following them, McLachlan & McMillan (1976), referred this upper fine-grained unit to the non-marine Kirkwood Formation. However, the Gamtoos Basin is a simple half-graben, essentially composed of a single compartment, and the MK 1/70 section is thus part of exactly the same succession as seen in the offshore Gamtoos boreholes. Consequently the finer-grained upper succession in MK 1/70 is here referred to the Portlandian, and is considered time-equivalent to the Bethelsdorp Formation of the Uitenhage Trough in the Algoa Basin. In borehole MK 1/70 the hyposaline portions of the succession are distinguished by the occurrence of small numbers of agglutinated benthic foraminifera of the genus *Haplophragmoides* (Fig. 5), but they provide no specific age indications. More exploration work needs to be undertaken to locate these foraminiferal assemblages in outcrop. It is as yet not known if the fluvial-to-hypsaline claystones outcrop at any clean, little-weathered sites along the Gamtoos coastline, along the lowest reaches of the Gamtoos River, or just inland of the coast, and, except for Rogers (1906), unfortunately Amm (1934), Frankel (1936) and Martin (1960) provide few relevant details on outcrop sites of this succession. It may prove possible to locate and sample thin marine bands much more efficiently in outcrop or shallow cored borehole, than in the cuttings borehole MK 1/70, with its problems of caving sandstones contaminating the microfossil-bearing claystones. Martin (1960) listed seven out of 30 recognised palynofossils in an outcrop sample from this Bethelsdorp-equivalent succession, and noted the assemblage is “closely comparable with Upper Jurassic and Lower Cretaceous ones and apparently lacking forms which seem to be typical of the Lower Cretaceous of Australia”.

The boundary between the Enon conglomerates and the overlying fine-grained (Bethelsdorp-equivalent) beds is an abrupt one in borehole MK 1/70, in keeping with the upper boundary of the basal clastic wedge almost everywhere in the Pletmos, Gamtoos and Algoa Basins. Consequently it is difficult to resolve this clear and abrupt lithological change with the comments of Haughton *et al.* (1937a),

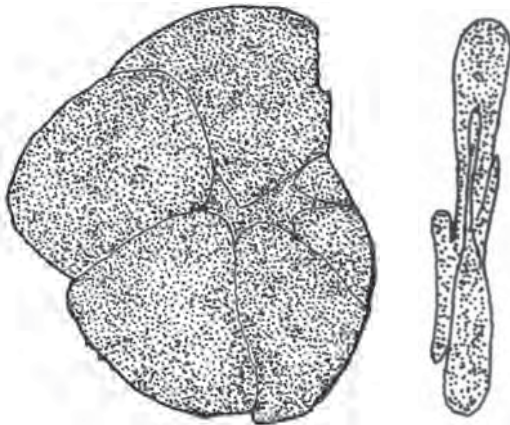


FIGURE 5

Haplophragmoides sp. 5.

Far left: SAM-PQ-MF 2350. Side view.
Gamtoos Basin borehole MK 1/70,
Core 2, 1701'. $\times 116$.

Left: SAM-PQ-MF 2350. Apertural view.
 $\times 116$.

reiterated by McLachlan & McMillan (1976, p.207), that Houghton *et al.* “were unable to subdivide the deposits into Enon and variegated marls as the two facies are too irregularly interbedded”.

In the offshore portion of the Gamtoos Basin ten boreholes have been drilled in a wide variety of basin settings. Again, there are variable, localised thicknesses of Enon conglomerates with some sandstones within a basal coarse clastic wedge, but in general the graben infill of this basin is fine-grained, and claystones predominate. Borehole Ha-H1 in the distal southwestern portion of the basin intersected 350m of interbedded sandstones and claystones in the basal clastic wedge (D to DCI interval) that represent the most distal intersection of the Enon conglomerate sedimentary phase yet drilled. Small agglutinated benthic foraminifera assemblages occur intermittently through the succession, dominated by conservative *Ammobaculites* and *Haplophragmoides* species, but also marked by numbers of *Tritaxia* tests. The genus *Tritaxia* is otherwise not seen in the South African Late Jurassic–Early Cretaceous succession in rocks older than Early Albian or Late Aptian. This singular *Tritaxia* assemblage is quite unlike the overlying Portlandian foraminifera assemblages of the Pletmos, Gamtoos or Algoa Basins.

In the Gamtoos Basin, seismic horizon DCI marks the top of the Kimmeridgian basal clastic wedge (top Enon conglomerates), seismic horizon P3 marks the top of the Portlandian Bethelsdorp equivalent, and seismic horizon J1 marks the mid Valanginian Kirkwood–Sundays River equivalent boundary. Seismic horizon P3 marks the top of distinctive and widespread high-gamma black claystones, which are often organic rich, but are unfortunately very poor in microfossils other than dictyomitroid and spherical radiolaria. It has proven difficult to microfaunally correlate this unit with coeval ones in the Pletmos Basin or the offshore Algoa Basin, because of the differences in depositional facies, and profound changes in the foraminiferal assemblages. In six Gamtoos boreholes seismic horizon J1 correlates with the first downhole appearance of the informal foraminifera zone species *Lagena* sp. (McMillan *et al.*, 1997, Fig. 3), which marks the first downhole appearance of Early Valanginian pre-Sundays River Formation foraminifera assemblages. Horizon 1At1 (previously horizon C) again lies in the upper part of the *Lenticulina coegaensis* foraminiferal Biozone B in the latest Valanginian (McMillan *et al.*, 1997, Fig. 3; McMillan, 2003a, Fig. 8), in northern borehole Ha-F1. However, further south in boreholes Ha-D1 and Ha-N1, the post-1At1 succession consists of upper bathyal dysoxic claystones: calcareous benthic foraminifera, including *Lenticulina coegaensis*, are absent, and only agglutinated benthic foraminifera and radiolaria are found (see McMillan *et al.*, 1997, Fig. 3).

Mbotyi and Mngazana Basins

These two small basins, constituting proximal parts of the mostly offshore Port St Johns Basin, reveal very different lithologies and lithofacies. Since there has

been, as yet, no deep offshore drilling in the Port St Johns Basin, the stratigraphic relationships between the Mbotyi and Mngazana graben successions remain unknown. Outcrops in the Mbotyi Basin reveal apparently non-marine mostly coarse greenish sandstones and pebble beds (sedimentary breccias, according to Karpeta (1987)), and some minor greenish-grey claystones, but up to now only carbonised wood has been found (McLachlan *et al.*, 1976b; Karpeta, 1987). Du Toit (1912, 1913) estimated a total thickness of about 300m for the succession in outcrop, while more recently Karpeta (1987) recorded a total of about 355m. The predominantly sandy outcropping succession presumably correlates with the Kirkwood Formation, although previous lithostratigraphic work suggested a correlation with the Enon conglomerates (Du Toit, 1976). The exclusively green colouration of the lithological succession (ferrous, reducing iron) suggests a fluvial depositional environment: it is not clear if gypsum rosettes in the succession are syn-sedimentary or diagenetic.

The graben fill exposed in outcrop in the Mngazana Basin consists of interbedded conglomerates, sandstones, limestone lenses and carbonate-cemented black claystones. Despite the coarseness of much of the succession, ammonites have been found (Klinger & Kennedy, 1979), and locally radiolaria are abundant (McLachlan *et al.*, 1976b; McMillan, 2003a), indicating a good connection with the open ocean at the time these sediments were laid down. Ammonites (Klinger & Kennedy, 1979; Cooper, 1983), ostracods (McLachlan *et al.*, 1976b; Brenner & Oertli, 1976; Valicenti & Stephens, 1984) and foraminifera (McLachlan *et al.*, 1976b; McMillan, 2003a) all show this succession to correlate with the mid Late Valanginian portion of the Sundays River Formation in the Algoa Basin. Du Toit (1912) provided early details for the outcropping succession, while Karpeta (1987) measured 50m of section. It is probable that equivalents of the Bethelsdorp Formation lie at depth in both basins, but perhaps only offshore, or downfaulted against the bounding faults. More study of these two basin fills is necessary.

Other Onland Basins

At present it remains unclear if dateable Late Jurassic successions occur in other Cape rifted basins, or how they are distributed. However, it is confident to assume that massive Enon-style conglomerates can be dated as part of the Kimmeridgian initial sedimentary episode wherever they may occur in these rift basins: in the Wellington, Robertson (Rastall, 1911; Söhnge, 1934), Swellendam, Langkloof, "Waterskilpads" (Malan & Theron, 1987), Hardevlakte, Knysna, Heidelberg-Riversdale (Viljoen, 1992), Oudtshoorn (Du Preez, 1944; Kleywegt, 1972; Holzförster, 2007), Plettenberg Bay (Bietou and Pisang Basins) and Mossel Bay Basins (Haughton *et al.*, 1937b). Furthermore, overlying fine-grained claystones, possibly high-gamma in character and whether red or grey in colour, hold promise as being part of the coarse-clastic-starved equivalent of the Portlandian Bethelsdorp Formation, may well be datable with a variety of techniques, and have

been recognised in the Mossel Bay, Heidelberg–Riversdale, Oudtshoorn, Gamtoos, and Pisang and Bietou Basins. Good summaries of outcrops in the Western Cape basins are given by Malan & Viljoen (1990). Typical thicknesses include at least 3000m conglomerates estimated, overlain with 150m of red greenish and blue mudstones, buff sandstones and small-pebble conglomerates in the Oudtshoorn Basin; up to 1460m of succession in the Mossel Bay Basin; more than 2133m of section in the Heidelberg–Riversdale Basin (Du Toit, 1954, p. 386; Rigassi, 1968; McLachlan & McMillan, 1976). Additional details of the onshore basins can be gained from Rogers (1905, 1910), Schwarz (1900, 1904, 1906, 1913) and Rogers & Schwarz (1900a, b, 1901, 1902).

Despite the localised occurrence of potentially fossiliferous Portlandian non-marine grey claystones overlying the Enon conglomerates, and the potential for biostratigraphy based on palynology, non-marine ostracods or charophyte oogonia, little progress has been made in fine-correlating these onland basins over the past 100 years. Much of the early work on *Estheria* (conchostracans) by Jones (1901) and on fossil plants by Seward (1903, 1907) from finer-grained rock units still has not been surpassed. In the late 1960s and early 1970s Midland Oil drilled one fully cored borehole in the Riversdale area (Riversdale 1) and two nearby cuttings boreholes (Eldorado, also known as PR-1A, or President 1; and PR-2 or President 2) that intersect varying thicknesses of graben fill in the Heidelberg–Riversdale Basin. Riversdale 1 recovered a graben fill succession of 462m of sandy and marly shales, conglomerates and breccia (McLachlan & McMillan, 1976). So far as is known these boreholes have never been formally studied for microfossils, although dark grey silty claystones occur in cores from Riversdale 1 and contain conchostracans. Conchostracans were also recognised at several sites around the town of Heidelberg (Rogers & Schwarz, 1902). It is not known if samples from the three boreholes still exist in storage.

MATERIAL

Borehole Material

The onshore Uitenhage Trough has been drilled by four deep boreholes, two of which reflect early local enthusiasm for oil exploration. The Swartkops borehole (now designated SW 1/08) was drilled in 1908–1909 by the Algoa Oil Company Ltd, on the coastal flats near the mouth of the Swartkops River, just to the north of Port Elizabeth, and was financed by local businessmen (Rogers, 1910; Smith, 1913). Its location is 33°52'47"S, 25°36'38"E. The presence of salt-pans in the region was regarded as a good indicator of oil, a feature used to site boreholes in the Galician oil-fields of Poland. A jumper drill and Galician drilling crew were brought in to drill the hole. It intersected 1106m of succession (basal Sundays River Formation; Kirkwood Formation; Bethelsdorp Formation; Swartkops Sandstone Formation; and possibly Enon Conglomerate Formation) before running into difficulties and terminating near to the top of the unconformably underlying Palaeozoic Table Mountain Group quartzites. The borehole failed to find any hydrocarbons, but encountered a strongly-flowing hot thermal spring near the base of the succession, whereupon a spa and sanatorium were built over the site of the borehole that lasted for much of the 20th century (Smith, 1913). These buildings have now been demolished (Shone, pers. comm.). An irregular series of samples was collected at the time of drilling from the borehole section, and are now held by the Port Elizabeth Museum, but they are severely depleted. Because of the style of drilling, some of these samples are contaminated with small proportions of Pleistocene dune sand containing Eemian-Weichselian benthic foraminifera. Various aspects of the geology of the SW 1/08 succession are dealt with by Rogers (1910), Smith (1913), Winter (1973) and McLachlan & McMillan (1976). (See Fig. 7 back cover pocket.)

Mr G.W. Smith, engineer in charge of drilling operations at SW 1/08 during 1908 and 1909, collected a set of samples at a variable interval down the borehole, some of which (probably the clearly fossiliferous portions) were sent to Dr F.L. Kitchin of the British Museum (Natural History), London, though the majority of the samples were later presented to the Port Elizabeth Museum. Through the courtesy of a former Director of the Museum, Dr J.R. Grindley, and with the help of Mr I.R. McLachlan, formerly of the Petroleum Agency of South Africa, small portions of the Port Elizabeth Museum samples were obtained for micropalaeontological processing. Little now remains of these samples, and the intervals between each

studied sample are very erratic. As a result, correlation of SW 1/08 results with those from BT 1/74 and ST 1/71 is only partially possible.

A second, shallower borehole exploring for oil was drilled in 1915 in the extreme proximal portion of the Uitenhage Trough, due south of Uitenhage town, by the Uitenhage Petroleum and Mining Company. Press reports for May 1916 report oil to have been found near Uitenhage: in fact, some time before January 1915 gas was found trapped within Early Pleistocene ("Alexandria Formation") bivalve shells obtained from three pits dug adjacent to the future borehole site. On the basis of the gas-bearing shells, the borehole was put down. This borehole, percussion-drilled near the northern boundary of the farm Naroës by the Armstrong brothers, and here designated NR 1/15, seems to have experienced considerable difficulties during drilling, perhaps because of lack of finance. Its location is approximately 33°8'1667"S, 25°38'33"E, on the southern margin of KwaNobuhle. It took about a year to reach a total depth of 1005 feet, intersecting lowest Kirkwood Formation and the upper half of the Bethelsdorp Formation. Details of the history of this borehole remain rather sketchy, but there is a South African Council for Geoscience report (Krige, 1942) that describes "oil" occurrences and the geology on Naroës, which summarises both the pits and the borehole and their lithology and stratigraphic section. In addition, samples of rock chips from parts of the succession, and fossil oysters (presumably from the Pleistocene "Alexandria Formation") are held in the collections of the Port Elizabeth Museum. Krige (1942) makes no mention of any fossils in the Uitenhage beds, and this is possibly due to both macrofossil shells and foraminifera tests being pulverised by the percussion drilling. The termination of NR 1/15 marked the end of private consortiums drilling for oil in the onshore Algoa Basin.

The NR 1/15 borehole intersected an interesting succession, which is very fine-grained, and probably displays high-gamma characteristics in parts. This succession can be correlated on its lithostratigraphy with the other borehole sections. Below the thin veneer of "Alexandria Formation" and pebbly soils encountered in the pits, and locally outcropping, are interbedded red, brown, yellow and grey clays and claystones ("variegated marls") of the basal Kirkwood Formation, but this lithological unit was not recognised in the borehole section, only in one of the pits. Stratigraphically below this (in the borehole section) is a 260 feet thick unit of "grey limestone clay", which equates to the non-marine "grey unit" seen in boreholes BT 1/74 and ST 1/71 overlying the Bethelsdorp Formation. Below this is 715 feet of "greenish soapstone", "dark blue carboniferous shale" and "grey Cretaceous clay", interspersed with rare thin sandstones and bituminous shales, which correlate with the upper half of the Bethelsdorp Formation as seen in BT 1/74 and ST 1/71 boreholes. The bituminous shales, at depths of 200 and 600 feet (Krige, 1942), are described as flammable, and probably have especially strong high-gamma electric log responses.

The third deep borehole in the Uitenhage Trough was ST 1/71, drilled by Soekor in 1971 at the height of that company's interest in the hydrocarbon potential of the onshore Algoa Basin. The location is 33°46'30"S, 25°32'00"E. It was drilled with a rotary drilling rig to a depth of 1921m: cuttings samples were recovered every 10m interval in the top half of the hole, and every 5m in the bottom half. This borehole was drilled on the farm Salt Pan, and it is sited close to the half-graben bounding fault (Coega Fault), so that it recovered the most complete graben-fill succession (1700m) of all four holes (lower half of the Sundays River Formation; Kirkwood Formation; Bethelsdorp Formation; (Swartkops Sandstone Formation not present); Enon Conglomerate Formation). However, the quality of the borehole is poor, and it experienced considerable cavings problems, so that Sundays River Formation foraminifera cave down into the Bethelsdorp Formation, and stratigraphic ranges of foraminifera gained from the Bethelsdorp Formation are sometimes not reliable. This borehole intersected 200m of Table Mountain quartzites at the base of the hole. The foraminifera of the portion of the Sundays River Formation intersected by ST 1/71 were part of the assemblages documented by McMillan (2003a). (See Fig. 8 back cover pocket.)

By far the best-quality rotary (cuttings) deep borehole was the final one drilled by Soekor in the onshore Uitenhage Trough, BT 1/74, sited on Bethelsdorp Commonage, on the north-eastern banks of the Bethelsdorp Salt Pan. The location is 33°51'08"S, 25°32'00"E. Using foraminifera assemblages, the borehole succession can be confidently correlated to the outcrops of the Bethelsdorp Formation occurring nearby in the low banks around the margin of Bethelsdorp Salt Pan. This locality is thus designated the outcrop stratotype of the Bethelsdorp Formation and BT 1/74 the type borehole section. The elongate outline of Bethelsdorp Salt Pan almost exactly overlies the outcrop of the Bethelsdorp Formation, and the salt-pan is presumably so located and orientated because of the restricted outcrop of the impermeable high-gamma claystones. The graben fill succession in BT 1/74 is about 771m thick (basal Kirkwood Formation; Bethelsdorp Formation; Swartkops Sandstone Formation; Enon Conglomerate Formation). This borehole has extremely clean, high-quality cuttings samples down to about 620m, where severe sloughing of the hole occurred. Without this quality borehole section it would not have been possible to define the variety of different foraminiferal assemblages occurring through the Bethelsdorp Formation succession. (See Fig. 6 back cover pocket.) After intersecting the graben fill, borehole BT 1/74 continued drilling deep into the Ordovician–Silurian Table Mountain Group quartzites, finally attaining a total depth of 2159m. Its aim in the Palaeozoic succession was exploring the potential for gas-bearing deep fractures or gas reservoirs. This was the last borehole drilled for hydrocarbons in the onshore Uitenhage Trough. More recent activity onshore has concentrated on the Sundays River Trough, developing exploration plays associated with the organic-rich claystones of the Colchester Formation, by Energy Resources and Mining Corporation in the late 1980s, and in the past five years by Exxoteq.

From the two Soekor boreholes, cuttings samples were available at 10m intervals (top-hole in both boreholes), 5m intervals (lower part of ST 1/71) and 3m intervals (lower part of BT 1/74). In all cases one cuttings sample was studied each 10m interval down these two borehole sections. In addition, four conventional cores were recovered from the Bethelsdorp Formation and the underlying Swartkops Formation in BT 1/74, and one core from the Bethelsdorp Formation in ST 1/71. One run of sidewall cores (12 useful recoveries) was made over the Bethelsdorp Formation interval of BT 1/74.

Outcrop Material

In addition to the borehole samples examined for foraminifera in the course of this study, thirty-five outcrop samples, collected by I.R. McLachlan and the late A.M. Anderson in the mid 1970s, were examined from the south-western margins of Bethelsdorp Salt Pan (29 samples), North End Lake (Korsten) (4 samples) and Chatty (2 samples). Most of these are brownish fine-grained claystones, but those with the greatest numbers of foraminifera tests often proved to be silty, very shelly sandstones (see vertical sections in McLachlan & McMillan, 1976, figs. 5 and 6). Small foraminifera assemblages were obtained from eight of the Bethelsdorp Salt Pan samples, but the remainder, and those from Chatty and North End Lake, were barren of *in situ* foraminifera. It has not proved possible to correlate the stratigraphic levels of the samples collected by McLachlan and Anderson to the lithological columns first described by Stow (1871), and redefined by McLachlan & McMillan (1976, fig. 6). Results of foraminifera studies on the borehole and outcrop samples are presented in range charts, Figs 6 to 10.

Two distinctly different foraminiferal assemblages were encountered in the productive samples from Bethelsdorp Salt Pan. In the sandy and shelly samples the foraminifera are exclusively calcareous, with robust, thick-shelled forms of the genera *Vaginulina*, *Planularia*, *Nubecularia* and *Fronicularia* predominating. In the brown silty clays, more thin-walled, delicate shells occur, with species of *Citharina*, *Lingulina*, *Pyramidulina* and *Epistomina* forming a sizable part of the assemblages. The sandy facies appears to have accumulated under littoral, open beach environments, while the clays seem to have accumulated in quieter waters, perhaps partly lagoonal, though still clearly marine, but also with a strong dysoxic influence on the sea-floor. As noted previously, the foraminifera of the outcrops at Bethelsdorp Salt Pan correlate with foraminiferal assemblage Peak 8 (the lowest peak recognised) especially in boreholes BT 1/74 and ST 1/71, on the basis of the very limited stratigraphic range of *Ammobaculites subaequalis* Mjatluk at all three sites.

Bethelsdorp Salt Pan is also known as the Mission Salt Pan, which is 28.4m above sea level, and is operated by Swartkops Sea Salt (Pty) Ltd, manufacturers of "Marina Sea Salt". The sampled outcrops on the south-western margin of the pan are 2.5 km

FIGURE 9

Microfaunal and macrofaunal results from Bethelsdorp Salt Pan. Samples listed in numerical order only.

| <i>microfauna/ macrofauna</i> | <i>sample no.</i> | <i>calcareous foraminifera</i> | <i>agglutinated foraminifera</i> | <i>free bryozoa</i> | <i>attached bryozoa</i> | <i>serpulid worm tubes</i> | <i>other worm tubes</i> | <i>?solitary corals</i> | <i>arthropod claws/shell</i> | <i>non-marine ostracods</i> | <i>marine ostracods</i> | <i>gastropods</i> | <i>Inoceramus prisms</i> | <i>Ostrea shell fragments</i> | <i>other bivalves</i> | <i>holothurian sclerites</i> | <i>echinoids spines/shell</i> | <i>crinoid ossicles</i> | <i>ophiuroid ossicles</i> | <i>indeterminate echinoderm shell</i> | <i>scaophopods</i> | <i>fish teeth</i> | <i>fish bone fragments</i> | <i>fish otoliths</i> | <i>fish scales</i> | <i>megaspores</i> | <i>wood fragments</i> | <i>barnacle plates/shell</i> | <i>?hexised</i> | |
|-----------------------------------|-------------------|--------------------------------|----------------------------------|---------------------|-------------------------|----------------------------|-------------------------|-------------------------|------------------------------|-----------------------------|-------------------------|-------------------|--------------------------|-------------------------------|-----------------------|------------------------------|-------------------------------|-------------------------|---------------------------|---------------------------------------|--------------------|-------------------|----------------------------|----------------------|--------------------|-------------------|-----------------------|------------------------------|-----------------|---|
| | 4798 | □ | - | □ | □ | - | □ | - | - | - | ▣ | ▣ | ▣ | □ | ▣ | - | ▣ | - | - | ▣ | □ | □ | - | - | □ | - | - | - | - | |
| | 4799 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | □ | - | - | - | - | - | - | - | |
| | 4800 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | |
| | 4801 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | |
| | 4802 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | |
| | 4803 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | |
| | 4804 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | |
| | 4805 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | |
| | 4806 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | |
| | 4807 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | |
| | 4808 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | |
| | 4808b | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | |
| | 4809 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | |
| | 4810 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | |
| | 4811 | - | - | - | - | - | - | - | - | - | - | □ | - | - | - | - | □ | □ | - | - | - | - | - | - | - | - | - | - | - | |
| | 4812 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | |
| | 4813 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | |
| | 4814 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | |
| | 4815 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | |
| | 4900 | - | - | - | - | - | - | - | - | □ | □ | ▣ | □ | - | □ | - | □ | - | ▣ | - | □ | - | - | - | - | - | - | - | - | |
| | 4901 | □ | - | ▣ | ▣ | - | - | □ | - | □ | ▣ | - | □ | ▣ | - | - | ▣ | □ | □ | ▣ | - | - | - | - | - | - | - | - | - | |
| | 4902 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | □ | - | - | - | - | - | - | - | - | - | - | - | |
| | 4903 | - | - | - | - | - | - | - | - | - | - | □ | - | ■ | - | - | □ | - | □ | - | - | - | □ | - | - | - | - | - | - | |
| | 4904 | □ | - | □ | □ | - | □ | □ | - | - | □ | □ | □ | ▣ | - | - | ▣ | - | ▣ | - | - | - | - | □ | - | - | - | - | - | |
| | 11475 | ▣ | - | - | - | - | - | - | - | - | ▣ | - | ▣ | - | □ | □ | ▣ | - | ▣ | - | □ | □ | □ | □ | ▣ | - | - | - | - | - |
| | 11476 | ▣ | - | - | - | - | - | - | - | - | ▣ | - | □ | - | □ | □ | □ | □ | ▣ | - | - | - | □ | - | □ | □ | - | - | - | - |
| | 11477 | ▣ | - | - | - | - | - | - | - | - | ▣ | - | - | - | - | □ | ▣ | - | - | ▣ | - | - | - | - | ▣ | - | - | - | - | - |
| | 11478 | □ | - | - | - | - | - | - | - | - | □ | □ | ▣ | - | □ | - | ▣ | - | ▣ | - | - | □ | - | □ | - | - | - | - | - | - |
| | 11479 | □ | - | - | - | - | - | - | - | - | □ | - | - | □ | □ | - | □ | □ | - | - | - | - | □ | - | - | - | - | - | - | □ |

| KEY | | | | |
|-----|-----|------|-------|-----|
| □ | ■ | ■ | ■ | ■ |
| 1 | 2-5 | 6-15 | 16-49 | 50+ |

FIGURE 10

Foraminiferal results from Bethelsdorp Salt Pan. Samples listed in numerical order only.

| <i>species/sample</i> | 4798 | 4901 | 4904 | 11475 | 11476 | 11477 | 11478 | 11479 |
|--|------|------|------|-------|-------|-------|-------|-------|
| <i>Frondicularia franconica</i> | 7 | 10 | 1 | – | – | – | 1 | 1 |
| <i>Bullopora laevis</i> | 1 | 1 | – | – | – | – | – | – |
| <i>Nubecularia lucifuga</i> | 2 | 5 | 1 | – | – | – | 1 | – |
| <i>Planularia madagascariensis</i> | 2 | 2 | – | 8 | 5 | 6 | – | 1 |
| <i>Tristix acutangulus</i> | 1 | 2 | – | – | 1 | – | – | – |
| <i>Tristix</i> sp. 1 | 1 | – | – | – | – | – | – | – |
| <i>Planularia beierana</i> | 4 | 6 | 3 | 3 | 7 | – | 1 | – |
| <i>Vaginulina barnardi</i> | 1 | 6 | 2 | 44 | 40 | 22 | 1 | 6 |
| <i>Ramulina fusiformis</i> | 1 | – | – | – | – | 1 | – | – |
| <i>Lagena algoaensis</i> | 1 | – | – | 4 | – | 1 | – | – |
| ? <i>Bullopora</i> sp. | – | 2 | 2 | – | – | – | – | – |
| <i>Citharina</i> sp. | – | 1 | – | 7 | 4 | 2 | – | 1 |
| <i>Neoflabellina</i> sp. | – | 1 | – | – | – | – | – | – |
| <i>Lingulina</i> spp. | – | 1 | – | – | 3 | – | – | – |
| <i>Lingulina nodosaria</i> | – | – | – | 1 | 1 | – | – | – |
| <i>Pyramidulina minuta</i> | – | – | – | 1 | 3 | 3 | – | – |
| <i>Citharina harpa</i> | – | – | – | 2 | 1 | 2 | – | – |
| <i>Citharina inconstans</i> | – | – | – | 4 | 3 | 3 | – | – |
| <i>Frondicularia</i> cf. <i>L. loryi</i> | – | – | – | 1 | – | – | – | – |
| <i>Pyramidulina</i> cf. <i>P. minuta</i> | – | – | – | – | 1 | – | – | – |
| <i>Pyramidulina</i> sp. | – | – | – | – | 2 | 2 | – | – |
| <i>Planularia</i> spp. | – | – | – | – | 2 | – | – | – |
| <i>Marginulina</i> sp. | – | – | – | – | 1 | – | – | – |
| <i>Ammobaculites subaequalis</i> | – | – | – | – | – | 1 | – | – |
| <i>Dorothia</i> sp. | – | – | – | – | – | 1 | – | – |
| <i>Ammobaculites</i> sp. 1 | – | – | – | – | – | 3 | – | – |
| <i>Epistomina parastelligera</i> | – | – | – | – | – | 7 | – | – |
| <i>Vaginulina</i> sp. | – | – | – | – | – | 1 | – | – |
| <i>Vaginulinopsis</i> spp. | – | – | – | – | – | 2 | – | – |
| <i>Haplophragmoides</i> sp. 6 | – | – | –8 | – | – | 4 | – | – |
| <i>Haplophragmoides</i> sp. 5 | – | – | – | – | – | 1 | – | – |
| <i>Pyramidulina</i> cf. <i>P. kuhni</i> | – | – | – | – | – | 1 | – | – |
| <i>Globulina prisca</i> | – | – | – | – | – | 2 | – | – |
| <i>Eoguttulina anglica</i> | – | – | – | – | – | – | – | 2 |
| ? <i>Tristix</i> sp. | – | – | – | – | – | – | – | 1 |

south-south-west from the site of borehole BT 1/74. It is not known how accessible the outcrops around the salt-pan sampled by Ian and Ann McLachlan in the mid 1970s now are, or even if they still exist. As indicated by McLachlan & McMillan (1976), the surroundings around North End Lake were landscaped in the early 1970s, and the latest Jurassic graben fill is no longer exposed there. Two grey claystone samples collected by McLachlan and Anderson from poor exposures at Chatty are associated with red beds, but no microfossils were obtained.

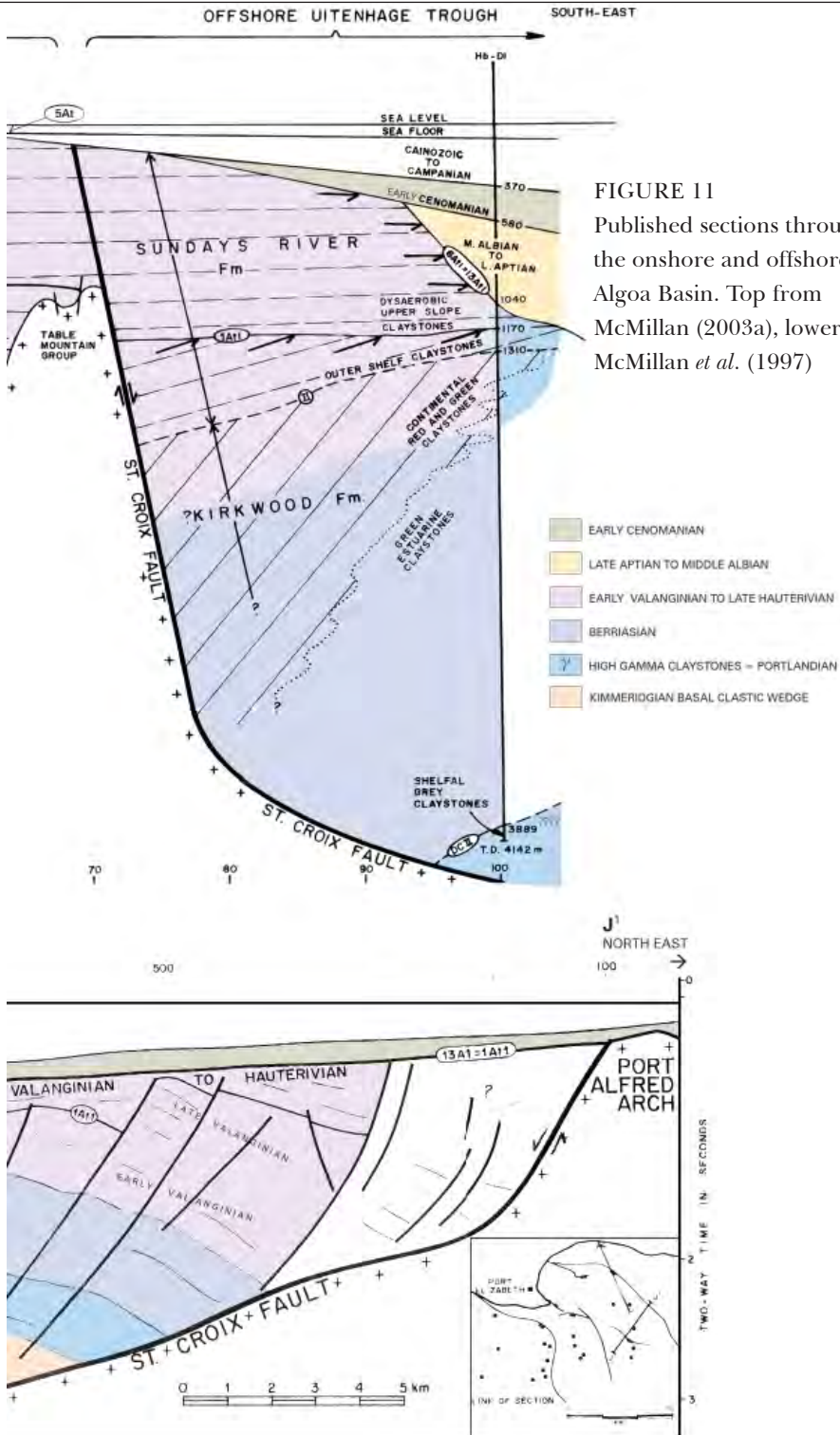
All borehole and outcrop samples were boiled in a solution of Tinegal PAC (a high-powered, large-molecule, quaternary ammonium detergent manufactured by Ciba Geigy) in water for about three-quarters of an hour. The samples were then washed free of mud using a 63 micron sieve, then residues dried and picked for microfossils in the normal micropalaeontological manner. All samples processed for foraminifera were of friable claystone, with variable silt or sand, or siltstone, and proved easy to process.

Microfossil Preservation

In general, the foraminifera assemblages of the Bethelsdorp Formation are not as well preserved as those of the Sundays River Formation (McMillan, 2003a). Many calcareous foraminifera tests from the Bethelsdorp Formation have been partially leached on their surface, resulting in roughening of the surface on both miliolid and nodosarid shells. This feature of the foraminifera tests may be due to the much greater depth of burial which the Bethelsdorp Formation attained at maximum burial at the end of the Hauterivian, when compared to that of the Sundays River Formation at the same time. However, poor preservation is not a consistent feature, and even in the sandiest samples from Bethelsdorp Salt Pan, for example, occasional beautifully preserved foraminifera tests do occur. Nonetheless, it is clear that the graben-fill sediment pile preserved today in the onshore Uitenhage Trough is only a portion of what was originally laid down, both in terms of thickness and areal extent. Ever since uplift of the graben succession and incision of the Algoa Canyon in Early Barremian times (McMillan *et al.*, 1997) there have been repeated uplift-erosion episodes that have progressively cut into the remnants of the succession, and uplifted the remainder back up to today's land surface.

Previous Work

Earliest work on the geology of the onshore Uitenhage Trough has been summarised by McLachlan & McMillan (1976, p.199 *et seq.*). Atherstone (1857), Tate (1867), Stow (1871), Newton (1914) and Haughton (1928) all comment on various aspects of the geology of the outcrops around Bethelsdorp Salt Pan and North End Lake. Oysters, echinoids, bivalves and gastropods were reported at Bethelsdorp Salt Pan by Stow (1871) who attempted to subdivide the marine succession into the (lower) "saliferous beds", as at Bethelsdorp Salt Pan, and the (upper) Uitenhage Formation (now the Sundays River Formation).



The singular occurrence of *Cidaris* echinoid shells and spines at Bethelsdorp and North End Lake was noted by both Atherstone and Stow. However, it was only with the work of Rigassi (1970, p. 16) and Rigassi & Dixon (1972) that a discrete lower marine unit was recognised in the onshore Uitenhage Trough, clearly distinct from the marine beds of the Sundays River Formation. Up to now, neither ammonites nor ammonite fragments are known from either outcrops or borehole sections in the Bethelsdorp Formation in the onshore Uitenhage Trough, an unfortunate absence.

The earliest microfossils recognised in the Bethelsdorp Formation were non-marine ostracods in samples from the SW 1/08 borehole, encountered during analysis of the macrofossils by Kitchin (in Rogers, 1910). Possible cyprid ostracods were seen in a sample at 2100 feet, while at 2500 feet clayey shale was found to be

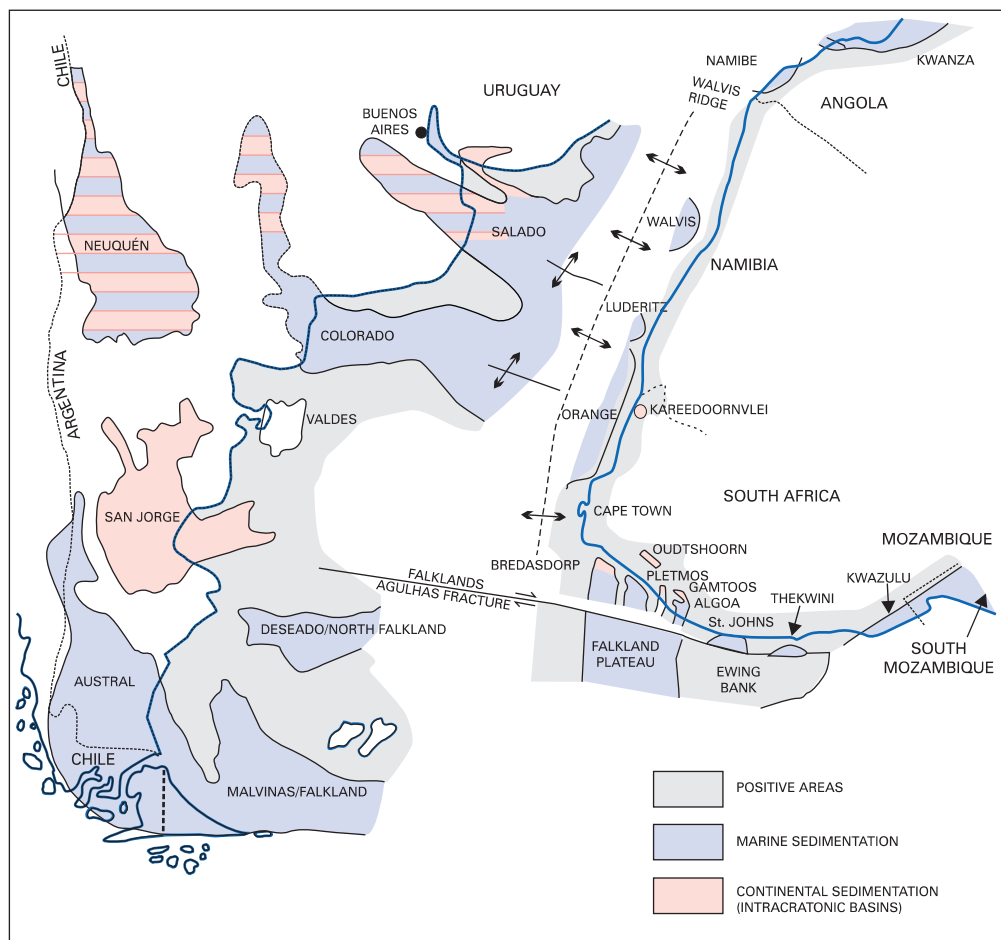


FIGURE 12

Late Jurassic–Cretaceous sedimentary basins of the southern South Atlantic Region (based on Malumián, 1990, fig. 1)

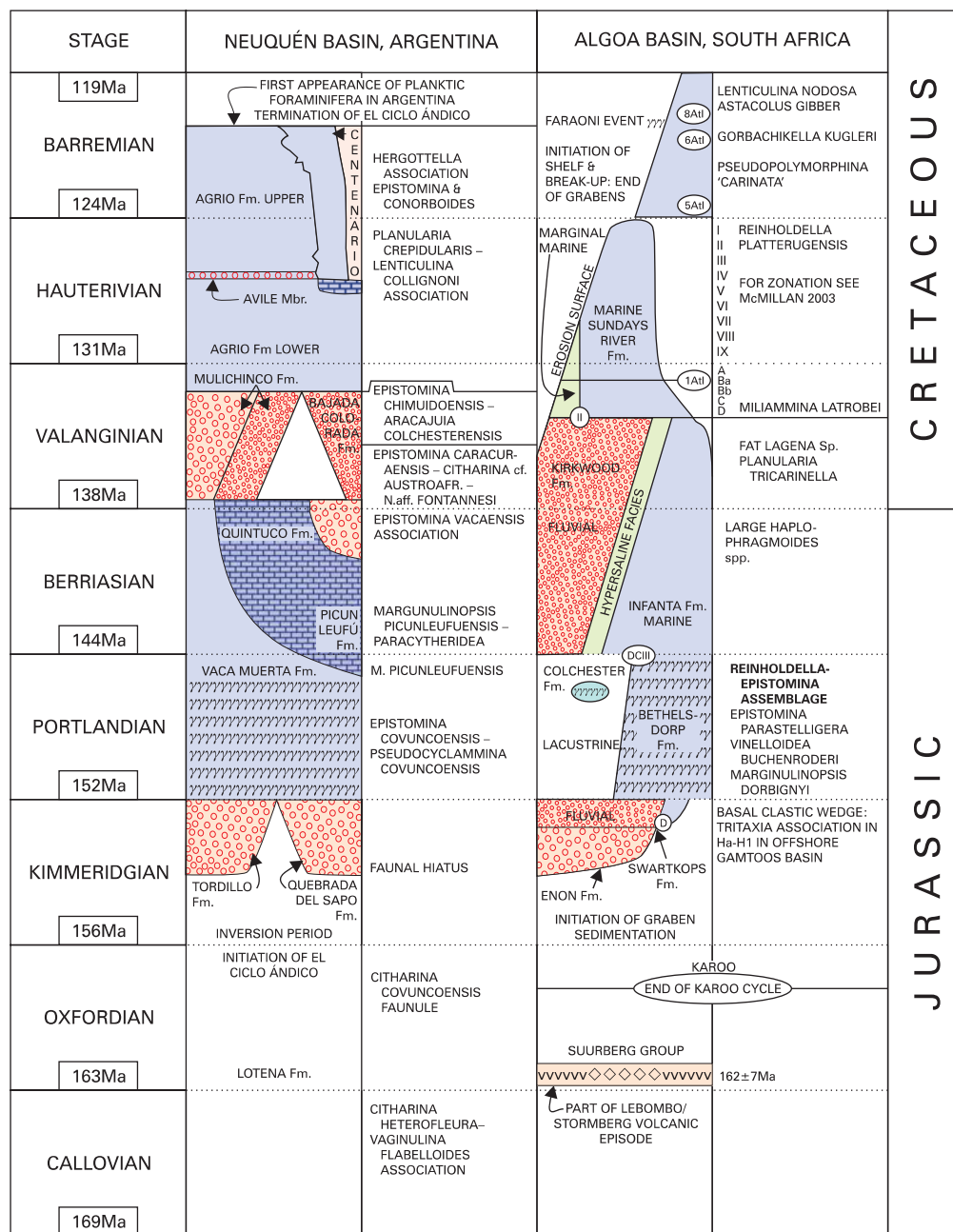
“crowded with cyprids; probably *Cypris* or *Cypridea*”. Kitchin compared the macro- and micro-fossils with those of the latest Berriasian to latest Barremian Weald Clay succession of southern England, though he pointed out that the palaeontological evidence was not decisive.

Rigassi (1970) and Rigassi & Dixon (1972) processed seventeen samples from the SW 1/08 borehole section. From one sample they identified *Epistomina* aff. *E. australiensis* Crespin, *Marginulina inconstantia* Cushman, “and other non-diagnostic species of foraminifera” at a depth of 2949 feet in the borehole – all other samples proved barren. Mainly on lithostratigraphic grounds Rigassi & Dixon (1972) considered this lower marine unit to be coeval with the Colchester Formation of the Sundays River Trough and to be of Berriasian to Early Valanginian age. Their correlation of the “Colchester Member” with the Brenton Formation was disputed by McLachlan & McMillan (1976, p. 209), and subsequent ostracod and foraminifera biostratigraphic analysis showed the latter formation to be equivalent to the basal Sundays River Formation (McLachlan *et al.*, 1976a; McMillan, 2003a). The ostracods, foraminifera and palynology were analysed in particular detail by McLachlan *et al.* (1974b) and McLachlan & Scott, 1972.

Borehole ST 1/71 was analysed microfaunally and palynologically by Robertson Research International (Bagnall *et al.*, 1971). They considered the “Colchester Member” section of ST 1/71 to be of Late Jurassic–Early Cretaceous age: more particularly in core 1 of the borehole (about 1400m), uppermost Jurassic ostracods (when compared with those of the Mahajanga (Majunga) Basin of north-west Madagascar) and Berriasian–Valanginian palynomorphs were recognised. Foraminifera from the same interval were not regarded as diagnostic: *Eoguttulina* sp., miliolids, *Haplophragmoides* sp., *Epistomina* cf. *E. caracolla* (Roemer), *Pseudoglandulina* sp., *Dentalina* sp., *Ammobaculites* sp., ?*Haplophragmoides* sp., *Trochammina* cf. *T. squamata* Jones & Parker, ?*Pseudoglandulina* sp., ?*Eoguttulina* sp., and strangely, *Gavelinella* sp. (the last-named is probably a contaminant).

Later work (Bagnall *et al.*, 1972), compiling all Algoa Basin results, concluded that it was not possible to correlate the “Colchester Member” using foraminifera. On the basis of the palynological assemblages from the “Colchester Member” of both the Uitenhage and Sundays River Troughs, an earlier Neocomian age was concluded.

More diverse and less caved foraminifera assemblages were encountered in the “Colchester Member” succession intersected in borehole BT 1/74, where the foraminifera were dominated by species of miliolids, together with species of *Ammobaculites*, *Haplophragmoides*, rare nodosarids, *Eoguttulina* and *Epistomina* (McLachlan *et al.*, 1974a). The age of the fossiliferous interval was initially regarded as Berriasian (Purbeckian). This sequence was later equated to the “Colchester Member” of offshore borehole PB-A1 by McLachlan *et al.* (1976a), and both units



KEY

- ∇ VOLCANICS
- ◇ BRECCIAS
- CONGLOMERATES
- SANDSTONES
- CLAYSTONES
- γ HIGH-GAMMA (HEMIPELAGIC) CLAYSTONES

LIMESTONES

UNCOLOURED AREAS MARK UNCONFORMITIES

- NON-MARINE ENVIRONMENTS
- MARINE ENVIRONMENTS
- LACUSTRINE ENVIRONMENTS
- HYPERSALINE AND HYPOSALINE MARGINAL MARINE ENVIRONMENTS

were regarded as ?Berriasian to Early Valanginian in age, though the foraminifera assemblages of the two regions are rather dissimilar, for depositional facies reasons. More recent work has suggested a Portlandian, latest Jurassic age for the foraminifera assemblages of the “Colchester Member” (McLachlan & McMillan, 1979, p.168). The present work stems from detailed taxonomic analysis of the foraminifera of the onshore Uitenhage Trough boreholes and outcrops, which was completed as an unpublished Soekor report by the author in 1980. This work included detailed analysis of the clear foraminiferal abundance peaks, and their varied taxonomic composition, presented herein. Since 1980, declining economic interest in the onshore Algoa Basin has led to an end to active foraminiferal biostratigraphy there.

FIGURE 13 (*facing page*)

Foraminifera based biostratigraphy and basin tectonic history of the Neuquén Basin, Argentina, and the Algoa Basin, South Africa, during the later Jurassic–earlier Cretaceous ‘Ciclo Ándico’. Boundary age-estimates are from Kent and Gradstein (1985), slightly amended. Neuquén foraminifera biozonation from Simeoni (2000); chronostratigraphy from Howell *et al.* (2005); Algoa foraminifera biozonation from McMillan (2003a)

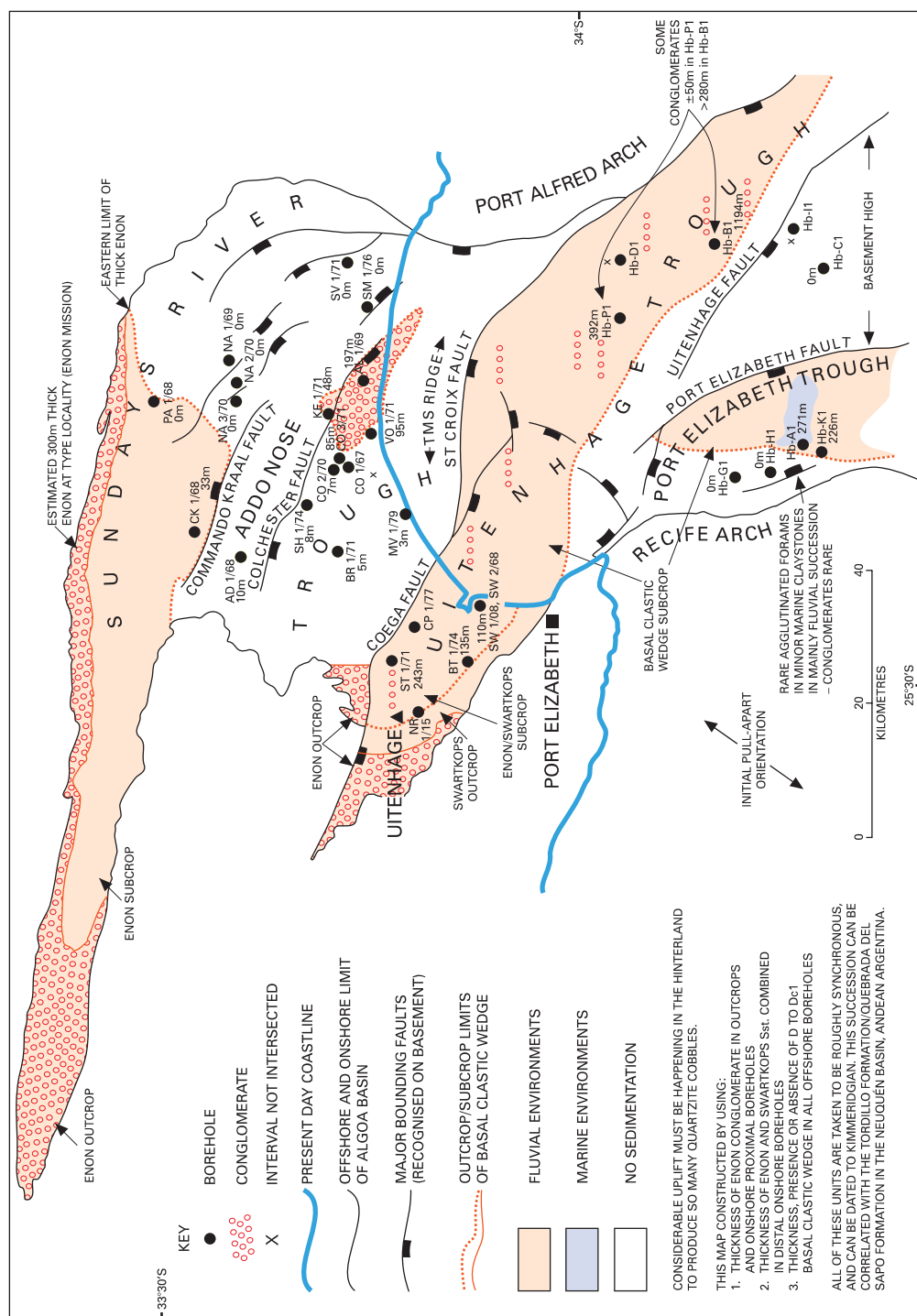


FIGURE 14

Initial subsidence in Algoa Basin: Kimmeridgian Basal Clastic Wedge (Enon/Swartkops phase)

STRATIGRAPHIC UNITS OF THE ALGOA BASIN

This section details the means by which the lithostratigraphic units identified in the proximal Algoa Basin are presently dated and correlated.

Enon Formation (Kimmeridgian)

The lithostratigraphic surface stratotype locality is at the Enon Mission Station in the northern Algoa Basin (Rigassi & Dixon, 1972; Winter, 1973). The estimated 300m thick type section has been described as red and white variably ferruginised conglomerates. Enon conglomerates are very localised in the southern Cape rift basins, but are much more widespread than any of the later units. They have been reported in the Worcester, Robertson, Swellendam, “Waterskilpads”, Hardevlakte, Heidelberg–Riversdale, Mossel Bay, Plettenberg Bay, Langkloof, Oudtshoorn, Gamtoos, Algoa and Mbotyi Basins. A silicified variant, the Robberg Formation (Rigassi & Dixon, 1972; Reddering, 2000, 2003) is known from the Robberg Peninsula at Plettenberg Bay. Additional mainly lithostratigraphic details are to be found in Houghton (1928, 1935) and Engelbrecht *et al.* (1962).

The Enon conglomerates have always been regarded as a coarser lateral and synchronous facies of the Kirkwood Formation red and green claystones with sandstones (for example, see McLachlan & McMillan, 1976, Fig. 2). However, although pebble beds do occur within the Kirkwood succession, and red clays and sands are present within the Enon conglomerate succession, on the basis of borehole sections and seismic sections, these two rock units must be of distinctly different ages.

As noted previously, in boreholes the uphole transition from conglomerate rock units to overlying claystones or sandstones is often extraordinarily abrupt, so much so that several seismic sequence boundaries lie at this level in the offshore Pletmos, Gamtoos and Algoa Basins. Unfortunately previous publications dealing with the Pletmos, Gamtoos and Algoa offshore basin successions are often based on incompletely drawn seismic sections, and the basal coarse clastic divergent wedge is curiously often not defined (Bate & Malan, 1992, figs. 2, 5, 6, 7, 9, 10 (the divergent wedge is Unit 1 in figs. 5, 6 and 7); McMillan *et al.*, 1997, figs. 17, 19 and 20; Paton & Underhill, 2004, figs. 5 and 7 (the wedge is part of the Earliest Syn-rift package)). Bate & Malan’s Unit 1 equates to the horizon D to O interval in the Pletmos Basin,

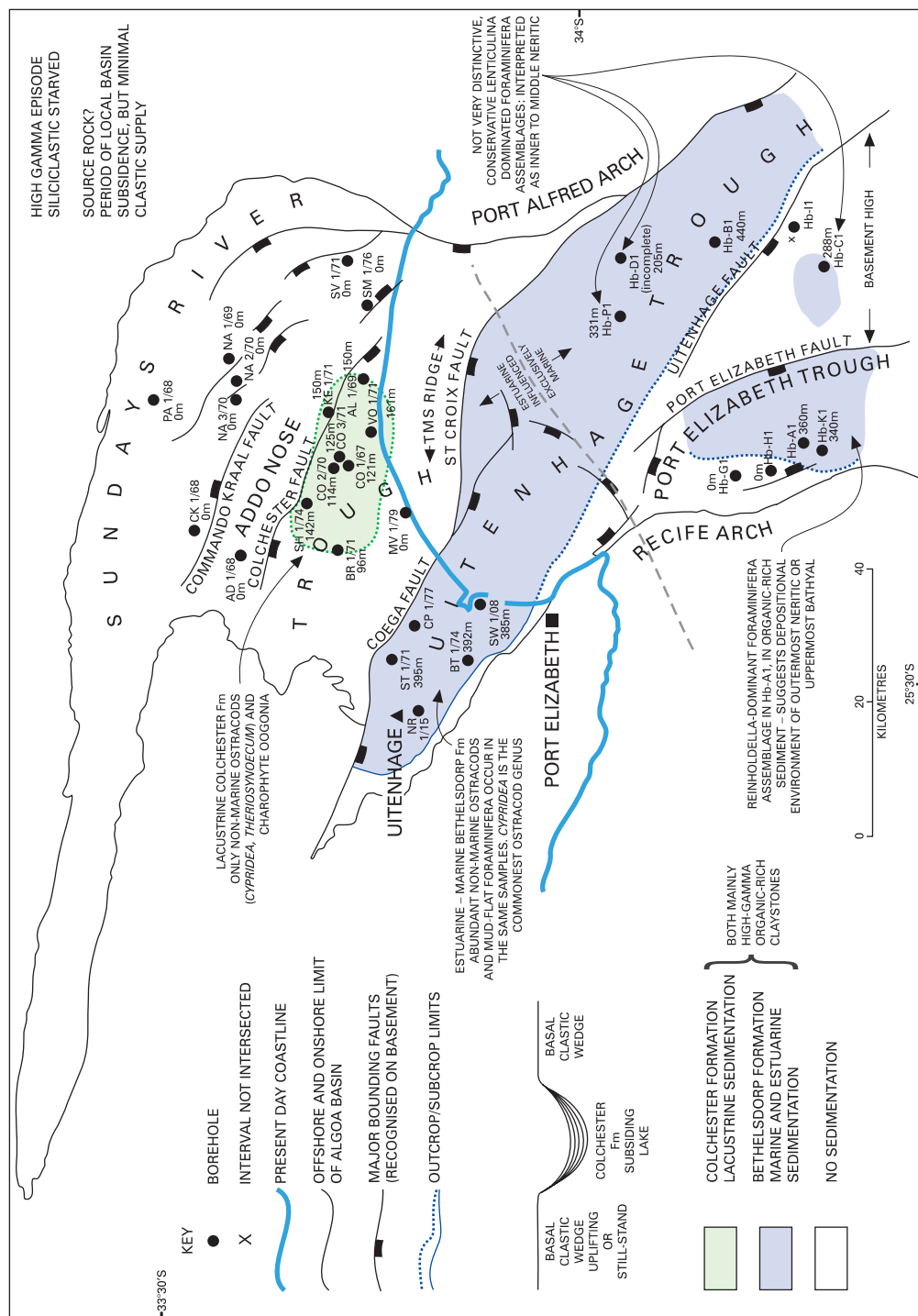


FIGURE 15

Subsidence in Algoa Basin during Portlandian (Bethelsdorp/Colchester) phase (mostly no sedimentation onshore) DCI to DCIII suggest localised subsidence of lake, uplift everywhere else

the horizon D to DCI interval in the Gamtoos Basin, and the horizon D to DCI interval in the Port Elizabeth Trough and offshore Uitenhage Trough, which are regarded as having accumulated synchronously with the mostly onshore Enon Formation. Thus the unconformity or sequence boundary identified as horizon O or horizon DCI in the offshore basins equates to the unconformity recognised in outcrop by Shone (1978) between the Enon conglomerates and the Kirkwood claystones and sandstones in the northern onshore Algoa Basin.

Nearly all outcrops and borehole intersections of the Enon Formation in the onshore and offshore Pletmos, Gamtoos and Algoa Basins expose rock successions that are interpreted as having accumulated in fluvial depositional regimes. Fossil wood occurs locally (see details in McLachlan & McMillan, 1976), and Mateer (1987) described dinosaur teeth from the Enon conglomerates of the Oudtshoorn Basin. The one clearly marine exception is the silicified conglomerates with fossil bivalve impressions, and black shales with agglutinated benthic foraminifera, outcropping at Robberg (Reddering, 2000, 2003). Offshore in the Algoa Basin, finer-grained fluvial successions of Enon conglomerates and sandstones have been intersected in boreholes Hb-B1 and Hb-P1 in the offshore Uitenhage Trough, and in boreholes Hb-A1 and Hb-K1 in the Port Elizabeth Trough. Although there are hints that some of the most distal, finer-grained Enon successions accumulated under marine, innermost neritic environments of deposition, most distal sections are still very sandy, if not pebbly, and *in situ* microfossils are rare, as in borehole Hb-A1 in the Port Elizabeth Trough. However, as discussed above, distal Gamtoos borehole Ha-H1 intersected a succession that is decidedly clayier than usual, and this yielded a small, but unique foraminifera assemblage distinguished by a singular species of *Tritaxia*. Although this benthic foraminiferal assemblage cannot be dated, it is clear that the “Enon Swartkops sedimentary episode” possesses a singular assemblage, quite unlike that of the overlying “Bethelsdorp/Colchester sedimentary episode”. In addition, the presence of a Kimmeridgian–Hauterivian graben-fill episode within the Jurassic–Cretaceous succession of the southern Argentina basins (Legarreta & Gulisano, 1991; Simeoni, 2000; Musacchio & Simeoni, 2008), especially evident in the Neuquén Basin, emphasises the close and similar stratigraphic history of the South African and Argentina basins (first noted by Kitchin, 1907), as well as confirming a maximum (Kimmeridgian) age for the South African graben infills. The Enon Formation equates to the Kimmeridgian Tordillo Formation/Quebrada del Sapo Formation, an episode of continental siliciclastics, in the Neuquén Basin of Argentina (Howell *et al.*, 2005).

Swartkops Formation (probably latest Kimmeridgian to earliest Portlandian)

Atherstone (1857) first used this term for unfossiliferous fluvial sandstones outcropping in the upper reaches of the Swartkops river valley, but the outcrop type locality is not defined. The subsurface stratotype was designated in borehole SW 1/08 by Winter (1973, 1979), but this borehole has no electric logs. The

Swartkops sandstone can also be recognised in BT 1/74 borehole, but is absent in borehole ST 1/71. There are localised comparable sandstones in a few of the boreholes drilled in the Sundays River Trough, such as in VO 1/71. No fossils of any type have been found in this unit, and consequently it has been inferred to be fluvial sandstone. Whether all these diverse occurrences correlate with the same, single rock unit cannot be established. The precise age of this unit is unknown.

The suggestion by McLachlan & McMillan (1976) that the shelly marine sandstones exposed at Bethelsdorp Salt Pan are referable to the Swartkops sandstones is not considered correct by the present author, and they are here considered part of the Bethelsdorp Formation.

Colchester Formation (Portlandian)

The Colchester Formation is limited to the central Sundays River Trough, onshore Algoa Basin. Winter (1973) stated that the stratotype of the Colchester Member in fully cored borehole CO 1/67 and adjacent cuttings borehole CO 2/70 consisted of about 80m of waxy grey shales. The Colchester Formation does not interfinger with the Kirkwood Formation at any site except possibly BR 1/71, where the Colchester interval is decidedly reddish. The Colchester Shale Member, described by Winter (1973), is here raised to formation level. The type section lies from 2171m (7100 feet) in fully cored borehole CO 1/67 (this borehole bottomed in the Colchester Formation, so its succession is incomplete), to 2243m in adjacent cuttings borehole CO 2/70. There is no surface stratotype section. The Colchester Formation can also be recognised in boreholes AL 1/69, BR 1/71, CO 2/70, CO 3/71, KE 1/71, SH 1/74 and VO 1/71, but is absent in all other borehole intersections in the Sundays River Trough. Its areal extent is consequently very limited. The Colchester Formation is probably bounded on its northern and eastern margins by the Colchester Fault, which defines the southern margin of the Addo Nose horst. The Colchester Fault was originally defined on the Palaeozoic basement surface using seismic sections (Battrick, 1974b), but what is probably the same fault outcrops at the surface, extending east-west from Centlivres railway station to Zoetgeneugd outcrop, and is shown on the geological map by Haughton (1928). The Colchester Formation onlaps the St Croix High, lying on the northward side of the St Croix Fault, in a southerly direction (Doherty, 1993; McMillan, 2003a, Fig. 2).

There is a faint possibility that the western tail-end of the Colchester Formation outcrops at the base of the Kirkwood Formation to the north-west of borehole BR 1/71, west of SH 1/74, and north-east of Coegaskop. However, the Colchester Formation is very red in colour in the intersection in borehole BR 1/71, although some organic-rich brown and black claystones do occur with non-marine ostracods and charophyte oogonia. In borehole MV 1/79 the Colchester Formation is completely missing, since the borehole is sited much higher on the upthrown northern flank of the Coega Fault. These characteristics suggest that the most promising area to

look for possible outcrops of the Colchester Formation is just south of the western end of the Colchester Fault, probably on the farms Glensomers or Prentjeskraal.

The Colchester Formation is interpreted to be of Portlandian age, from its similar stratigraphic position to the Portlandian foraminifera-bearing Bethelsdorp Formation. Although its non-marine and marine ostracods and charophyte oogonia have been studied in great detail by P.W. Brenner and V.H. Valicenti, this work has never been published, and remains as Sockor internal reports. The Colchester Formation is regarded as time-equivalent to the basal Vaca Muerta Formation of the Neuquén Basin, southern Argentina (Howell *et al.*, 2005)

Bethelsdorp Formation (Portlandian)

So far as is known, the first to consider that the “Colchester Member” of the Sundays River Trough and the onshore Uitenhage Trough should be better separated into two distinct lithological units, one in each trough, because of the clear differences in thickness, colour, lithology and in depositional environment between the two, were I.R. McLachlan, and later V.H. Valicenti: they both also proposed the name Bethelsdorp Formation. This unit equates to the “Saliferous Series” of Stow (1871).

The Bethelsdorp Formation attains a thickness of a little less than 400m in boreholes BT 1/74, ST 1/71 and SW 1/08 in the onshore Uitenhage Trough. A comparable thickness is exposed at the surface in a broad swathe close to the southern boundary of the Uitenhage Trough, which includes the sampled outcrop sites at Chatty, North End Lake and Bethelsdorp Salt Pan. The base of the Bethelsdorp Formation lies unconformably on a surface of Enon conglomerates and Swartkops sandstones. From the base to the top the Bethelsdorp succession is slightly regressive, and shows slight shallowing-upward in its depositional environment, as evident in borehole BT 1/74.

The Bethelsdorp Formation is here proposed as a discrete lithological unit of the proximal Uitenhage Trough, coeval with the Colchester Formation of the Sundays River Trough, and essentially of Portlandian age. It differs from the Colchester Formation in its overall marine-influenced depositional environment, in its variegated reddish, greenish or greyish-blue colour and in its unusually fine-grained claystone lithology. The very low cliff outcrops around the southern margins of Bethelsdorp Salt Pan are proposed as the stratotype locality (roughly 33°53'09"S, 25°31'55"E), which have been described in some detail by McLachlan & McMillan, 1976, p. 199–202, fig. 5). The proposed subsurface stratotype is the almost 400m thick intersection in cuttings borehole BT 1/74. This borehole lies only about 300m from the shore of Bethelsdorp Salt Pan, and it is probable that depositional environments and lithologies are very similar at the two sites. Because of the absence of any *in situ* foraminifera in studied samples from both North

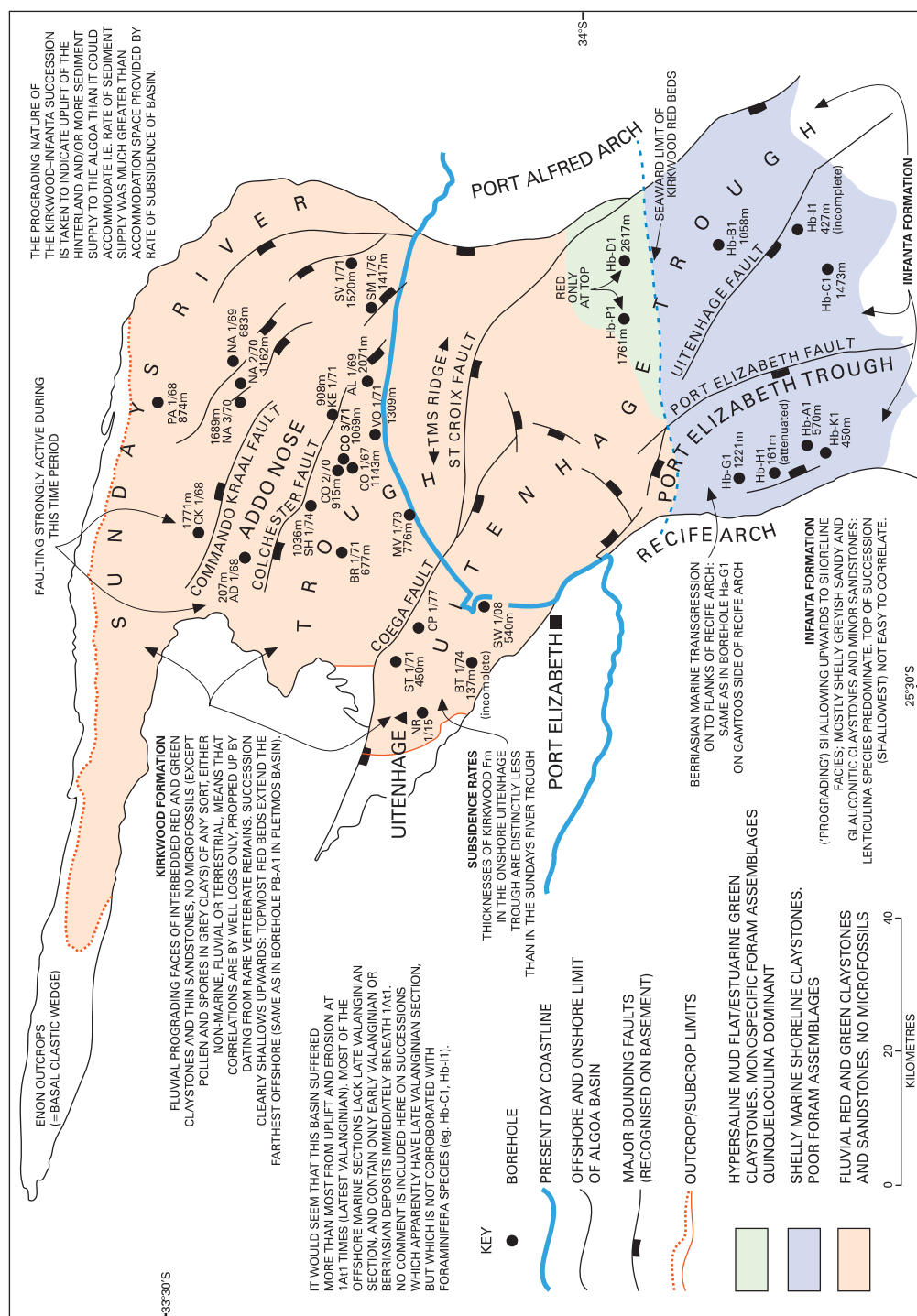


FIGURE 16
Subsidence in Algoa Basin during Berriasian–early Valanginian (Kirkwood/Infanta phase)

End Lake and Chatty, these two potential outcrops of the Bethelsdorp Formation may only be considered as possible comparable sections. However, there may be additional outcrops close to the southern margin of the Uitenhage Trough, despite widespread Pliocene and Pleistocene covering sandy veneers, all the way from the northern suburbs of Port Elizabeth westwards to the southern suburbs of Uitenhage town.

As discussed in more detail below, the foraminifera species recovered from shelly clayey sands and sandy clays exposed at Bethelsdorp Salt Pan in samples 11475, 11476 and 11477 show clearly that these samples derive from the lowest beds of the Bethelsdorp Formation, as intersected in borehole BT 1/74. The gamma ray log from the well completion report compiled by A.J. Battrick (1974a) for the relevant section of borehole BT 1/74 is shown in Fig. 19. High gamma claystones are developed throughout the Bethelsdorp Formation in the type borehole section in BT 1/74, as well as in borehole ST 1/71. The same characteristic can be recognised in the time-equivalent succession in the offshore Uitenhage Trough borehole sections Hb-B1, Hb-P1, and in the attenuated interval in Hb-D1, drilled prior to intersecting the St Croix Fault plane (see McMillan, 2003a, Fig. 2).

The Bethelsdorp Formation is coeval with the dark bituminous shales and marls (Weaver, 1931) of the lower Vaca Muerta Formation in the Neuquén Basin succession, southern Argentina. Doyle *et al.* (2005, p. 186) describe the Vaca Muerta as concordantly overlying the clastic and continental deposits of the Tordillo Formation (Enon equivalent). The top of the Vaca Muerta Formation is locally diachronous and progradational, but elsewhere unconformably underlies the non-marine siliciclastics of the Mulichinco Formation (Kirkwood equivalent) (Howell *et al.*, 2005).

Kirkwood Formation (probably Berriasian to Early Valanginian)

The Kirkwood Formation was described from the localities around Kirkwood Bridge (Rigassi & Dixon, 1972; Winter, 1973). There is a borehole stratotype: 1027 to 2171m in borehole CO 1/67 (Winter, 1979). The succession has been interpreted as having accumulated in a fluvial or coastal plain setting (McLachlan & McMillan, 1976; Shone, 1976, 1978). Fossil plants and resin occur locally (Seward, 1903; Brown & Gow, 1976; Brown, 1977a, b; Anderson & Anderson, 1985; Bamford, 1986; Gomez *et al.* 2002a, b; and Bamford, 2004). Pollen and spores were detailed from some samples from the Kirkwood Formation in boreholes CK 1/68 and CO 1/67 by Scott (1971, 1976). Numbers of vertebrates have also been described (Broom, 1904, 1910; Andrews, 1910; Galton & Coombs, 1981; Rich *et al.*, 1983; Forster *et al.*, 1995; Cruickshank, 1997; De Klerk *et al.* 1997; 2000a, b; Ross *et al.*, 1999; and Forster *et al.*, 2009). None of these fossils provide very accurate ages for the Kirkwood Formation, nor is there yet a biostratigraphic zonation. No marine indicators such as foraminifera or marine ostracods, or fluvial indicators

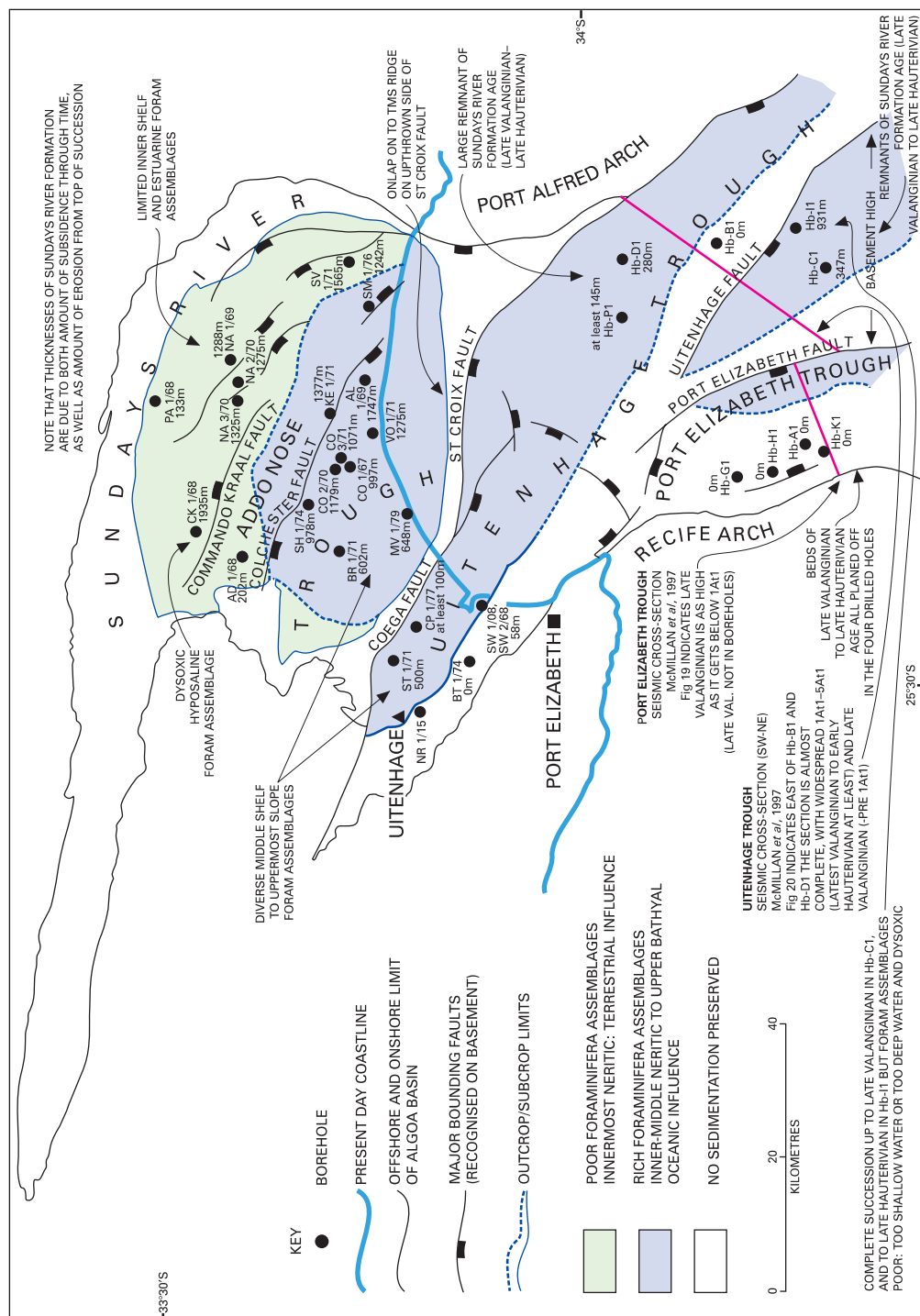


FIGURE 17
Subsidence in Algoa Basin during late Valanginian–late Hauterivian (Sundays River phase)

such as megaspores or non-marine ostracods (except the latter occasionally in the AD 1/68 borehole section) have been found in the Kirkwood succession, and much of the succession appears to be essentially barren of microfossils. Intersections of the most distal Kirkwood Formation in offshore boreholes (Algoa Basin boreholes Hb-D1 and Hb-P1, Gamtoos Basin borehole Ha-F1 and Pletmos Basin borehole PB-A1) show interfingering of foraminifera-bearing (*Haplophragmoides*) marine grey claystones and non-marine red or green claystones. The highest part of the Kirkwood Formation remains red the furthest offshore (McLachlan *et al.*, 1976b; McMillan, 2003a, Fig. 2) both in Algoa boreholes Hb-D1 and Hb-P1, and in Pletmos borehole PB-A1, indicating a slight shallowing up motif to the Kirkwood succession.

The Kirkwood Formation is presently essentially dated only on the basis of ages from the overlying Sundays River Formation and underlying Bethelsdorp Formation. The essentially Berriasian to Early Valanginian Kirkwood Formation marks a major regressive episode in the sedimentation history of the southern Cape grabens. The continental siliciclastics of the Mulichinco Formation constitute a major non-marine unit beneath the Agrio Formation (Sundays River equivalent) in the Neuquén Basin in southern Argentina (Howell *et al.*, 2005), and are regarded as being contemporary with the Kirkwood Formation.

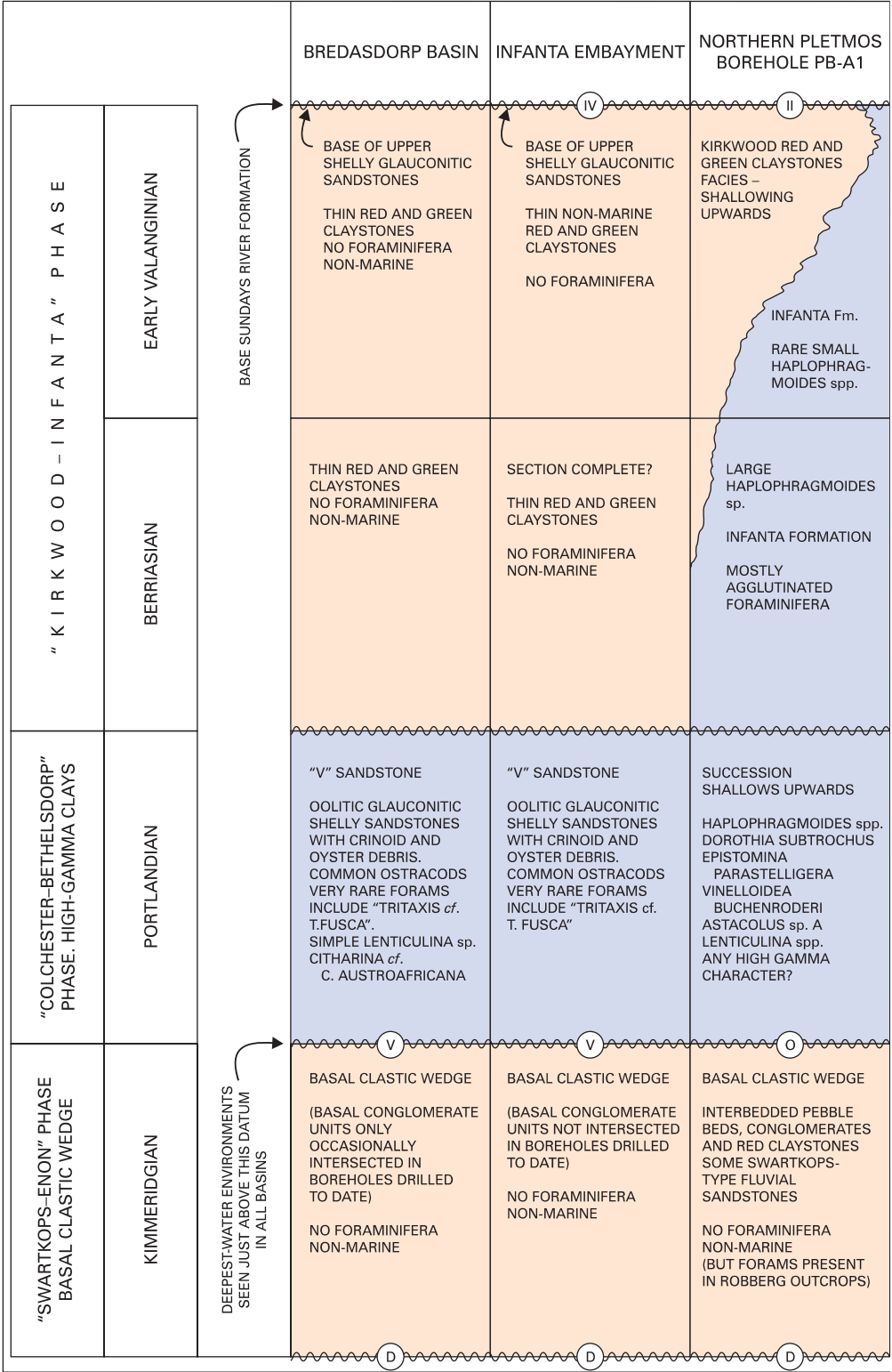
Sundays River Formation (Late Valanginian to latest Hauterivian)

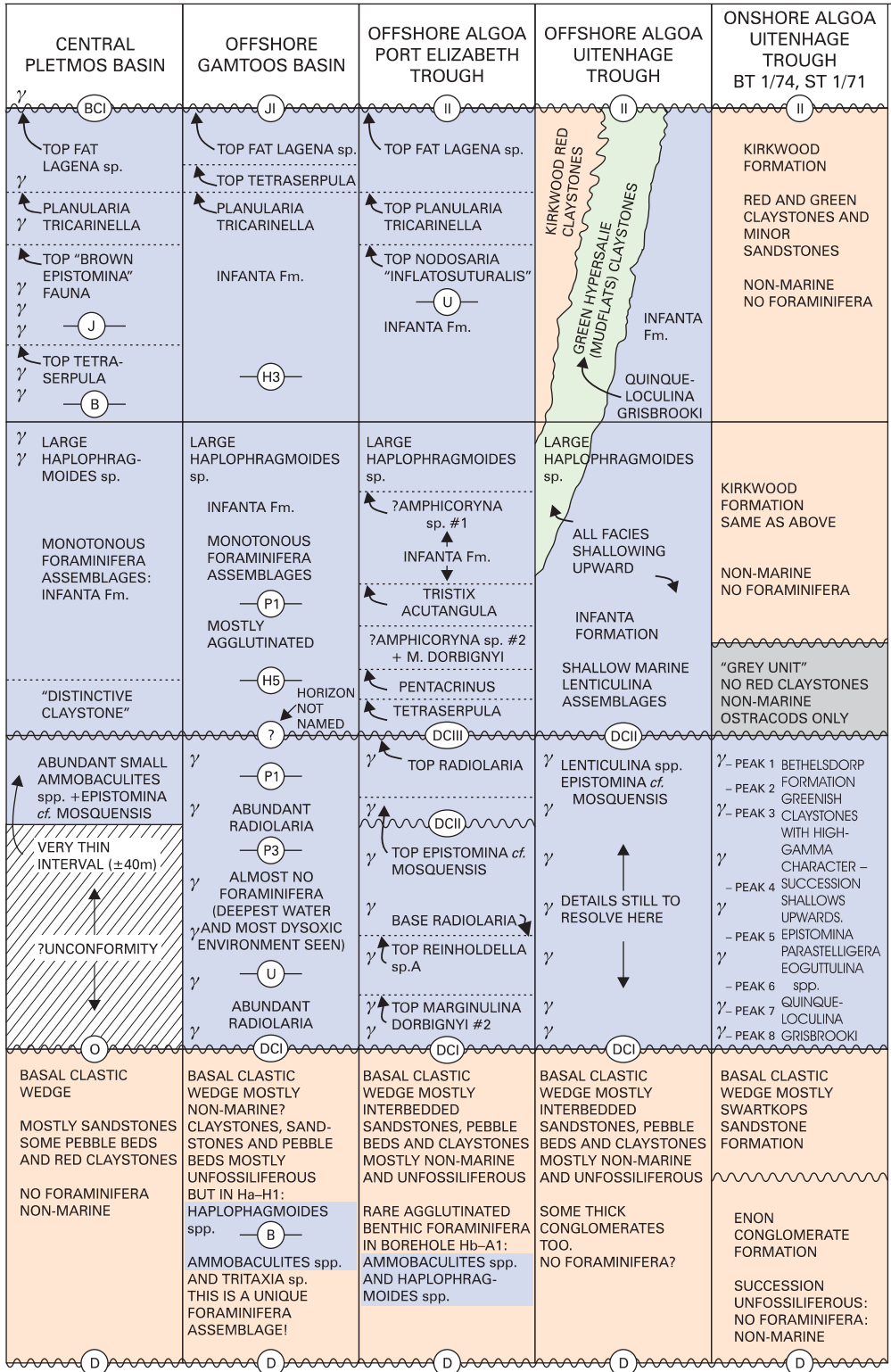
The outcrop stratotype is designated the high cliffs at Zoeteneugd on the Sundays River by Winter (1973). The borehole stratotype is designated the CO 1/67 section by Winter (1973, 1979), although borehole AL 1/69 includes about 380m extra section at the top of the Sundays River Formation, not seen in CO 1/67. Ammonites were last reviewed by Cooper (1981, 1983), and aspects of the bivalve assemblages also detailed by Rennie (1934), Pringle (1960) and Cooper (1979a, b, 1991). The ostracods were described by Dingle (1969), Brenner & Oertli (1976) and Valicenti & Stephens (1984), and reviewed by Dingle (1996), and the foraminifera by Rigassi (1970), Beer (1970) and McMillan (2003a). The age implications presented in these publications are essentially in accordance.

The Sundays River Formation in the Sundays River Trough accumulated in progressively less marine environments northwards (McLachlan & McMillan, 1976; Shone, 1976, 1978), and there is a marked decline northwards in the abundance and diversity of normal marine ostracods and the appearance of species typical of marginal marine conditions (Dingle, 1969, 1996; Brenner & Oertli, 1976; Valicenti & Stephens, 1984). There is a similar decline in abundance and diversity of benthic

FIGURE 18 (*overleaf – pages 50 and 51*)

Seismic horizons and foraminiferal zone markers for the lower portions of the graben fills in the major southern offshore basins





foraminifera northwards, with the calcareous-shelled forms disappearing first and the hyposaline-tolerant agglutinated-shelled forms later (McMillan, 2003a). Several northern borehole sections of the Sundays River Formation such as NA 1/69, drilled in the Nanaga area, are almost completely devoid both of foraminifera and ostracods, as well as macrofossils (Brenner & Oertli, 1976; McMillan, 2003a), but lithology colours remain grey or greenish-grey claystones. Although the marine fossil elements disappear, leaving only sparser estuarine, hyposaline ones (such as oysters, agglutinated foraminifera of the genera *Miliammina*, *Haplophragmoides* or *Ammobaculites*, and marginal marine ostracods), there seems to be no location (either in outcrop or borehole section) yet found where the Sundays River Formation grades laterally into fluvial red and green claystones. Consequently, there appears to be no lateral gradation between the “Kirkwood” red and green claystone facies and the “Sundays River” grey and greenish-grey claystone facies (see McLachlan & McMillan, 1976; Shone, 1978; McMillan, 2003a) preserved in the surviving rock record.

Analysis of foraminiferal assemblages from the various studied boreholes (McMillan, 2003a) that intersect the Sundays River Formation show that the change from diverse middle to outer neritic calcareous (aragonitic and calcitic shelled) benthic foraminifera assemblages to more monospecific or limited inner neritic, littoral or hyposaline assemblages is a relatively abrupt one, that occurs between borehole sections. There appears to be no borehole section yet drilled that intersects both middle to outer neritic as well as inner neritic or intertidal assemblages, suggesting there were no major alterations of sea-level during the Late Valanginian to Hauterivian period. Boreholes such as NA 1/69, NA 2/70, NA 3/70, NA 4/87 and DO 1/88 all drilled successions that accumulated in probably intertidal or mud-flat environments throughout the full thickness of the Sundays River Formation. This suggests that facies packages in the Sundays River Formation are more or less vertically stacked, in contrast to those of the Bethelsdorp, the Kirkwood and Infanta Formations, which are obliquely stacked, and consequently show shallowing upward.

The Sundays River Formation is considered to be a lateral equivalent of the marine siliciclastics, claystones and carbonates of the Agrio Formation (Howell *et al.*, 2005) in the Neuquén Basin of Argentina. The Agrio succession is divided into two by the continental or marginal marine sandstones of the Avilé Member, a feature that has not been identified in the Sundays River succession. On the basis of foraminifera, ammonites and nannofossils, the Agrio Formation appears to range from the latest Valanginian to the Early Barremian (Howell *et al.*, 2005; Aguirre-Urreta *et al.*, 2005), whereas on the basis of ostracods, ammonites and foraminifera the Sundays River Formation ranges from mid Valanginian to nearly topmost Hauterivian (Brenner & Oertli, 1976; Cooper, 1981, 1983; Valicenti & Stephens, 1984; McMillan, 2003a).

FORAMINIFERAL ASSEMBLAGES

The foraminifera assemblages of the Bethelsdorp Formation are unlike those of the Sundays River Formation and its time-equivalents (Beer, 1970, McLachlan *et al.* 1976a, b; Stapleton & Beer, 1977; McMillan, 2003a). Foraminiferal assemblages of the Bethelsdorp Formation are generally less diverse than those of the Sundays River Formation, simply because the latter encompasses a much wider array of depositional facies than does the former, which is limited to hyposaline estuarine, marginal marine and inner shelf. Similar shallow marine depositional environments can be seen in the more northerly offshore boreholes such as Hb-D1 (McMillan, 2003a, Fig. 2), and some of these beds are coeval with the Kirkwood Formation. However, it is only in the south of the offshore Algoa Basin, particularly in boreholes such as Hb-K1 and Hb-A1 in the Port Elizabeth Trough, and borehole Hb-B1 in the offshore Uitenhage Trough, that moderately-diverse foraminifera assemblages are encountered, some typical of dysoxic outer neritic or even upper bathyal environments.

The variety of foraminifera assemblages of the Bethelsdorp Formation in boreholes BT 1/74, ST 1/71 and SW 1/08 and in the Bethelsdorp Salt Pan outcrop reflect various estuarine, mudflat, littoral and inner neritic environments, with their concomitant differences in salinity, energy levels, and sediment substrate type. Palaeolatitude reconstructions for the Portlandian period by Smith & Briden (1977) indicate that the south coast of South Africa then lay at about 53°S. Foraminifera assemblages of the Bethelsdorp Formation are considered to reflect cool temperate marine conditions. The overwhelming majority of benthic foraminifera species in both the Bethelsdorp and Sundays River Formations possess smooth unornamented tests. In contrast, the majority of species detailed by Espitalié & Sigal (1963b) from the Late Jurassic to Early Cretaceous succession of the Mahajanga Basin in north-west Madagascar, are strongly ornamented with ribs, reticulations, tubercles, and so on. This considerable difference appears real: does it imply, for example, a biotic response to high sea-floor energy levels caused by currents and swells?

The great majority of the Bethelsdorp Formation in the onshore Uitenhage Trough appears to have accumulated in an unusually fine-grained mudflat or salt-marsh environment, since the foraminifera assemblages occur in a complex conjunction with fluctuating but often abundant numbers of non-marine and inner neritic

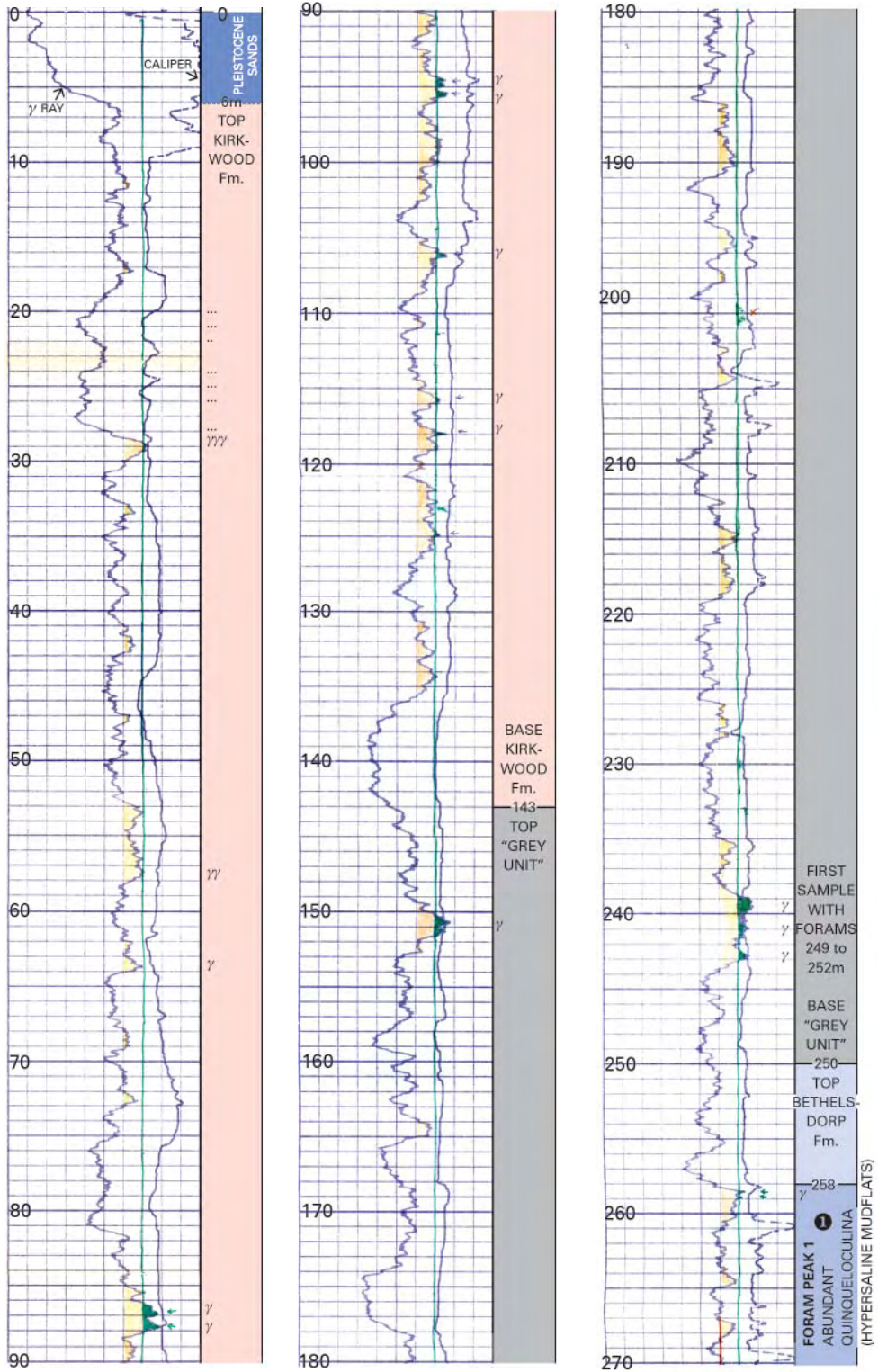
ostracod valves and carapaces (mainly of the genera *Cypridea* and *Progonocythere* (Valicenti)), and more occasional numbers of charophyte oogonia. The foraminifera assemblages tend to be overwhelmingly dominated by the single species of free-living miliolid *Quinqueloculina grisbrooki* sp. nov. Tests of this species are found in considerable numbers in all three studied boreholes, in the Bethelsdorp Salt Pan outcrop samples, and offshore in the lower Kirkwood Formation equivalent (green claystones) in borehole Hb-D1. That a free-living miliolid species is the dominant species through most of the Bethelsdorp Formation suggests an environment subject to profound salinity changes, with a frequent tendency towards hypersalinity, probably stemming from strong coastal winds evaporating thin sea-water films over the mudflats at low tides. In addition, the tests of *Quinqueloculina grisbrooki* frequently display considerable distortion, so that they lose their orderly quinqueloculine chamber arrangement, and become wild-growing, or even occasionally uncoiling. Malformed miliolid tests of this type also occur at the present day, especially in lagoonal environments regarded as highly stressful (Murray, 1973; Boltovskoy & Wright, 1976). This predominance of *Quinqueloculina* is not seen anywhere else in South Africa in time-equivalent successions of the Bethelsdorp Formation.

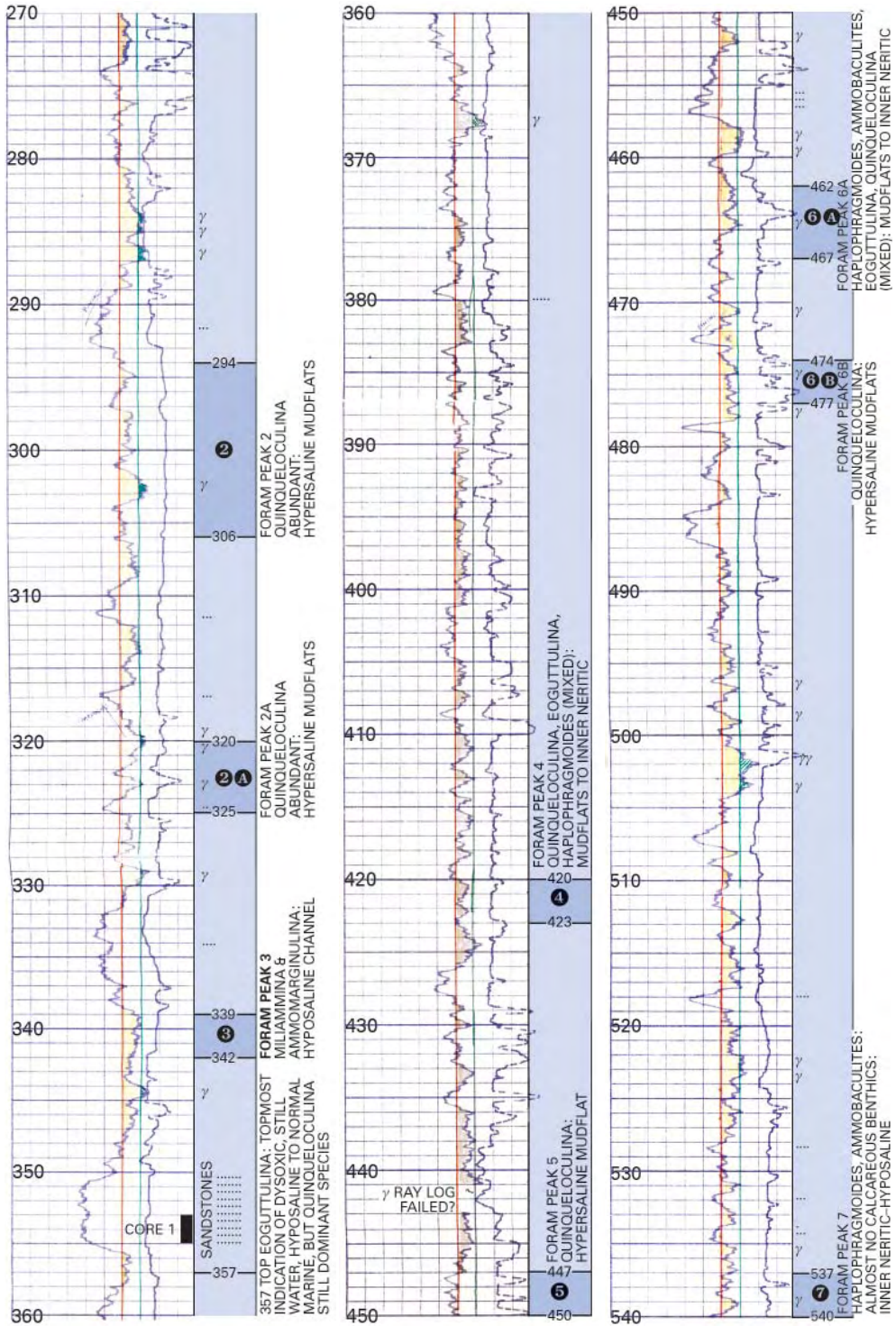
In contrast, there are occasional bursts of agglutinated foraminifera in which species of *Miliammina* predominate, especially at levels in the upper part of the formation. These *Miliammina*-rich assemblages are interpreted to reflect hyposaline environments developed either in channels crossing the mudflats, or in the main riverine channels. These localities would have experienced saline influence only at high tide. A similar assemblage dominated by agglutinated foraminifera is characterised by the species *Ammomarginulina missionensis* n.sp. (with *Miliammina* spp.). An extant similar genus, *Ammotium*, is usually found limited to either mangrove-swamp mud-flats or other specific tropical mud-flat environments. *Ammomarginulina* is thus interpreted to have occupied an unknown specific mud-flat environment, unlike those others described above.

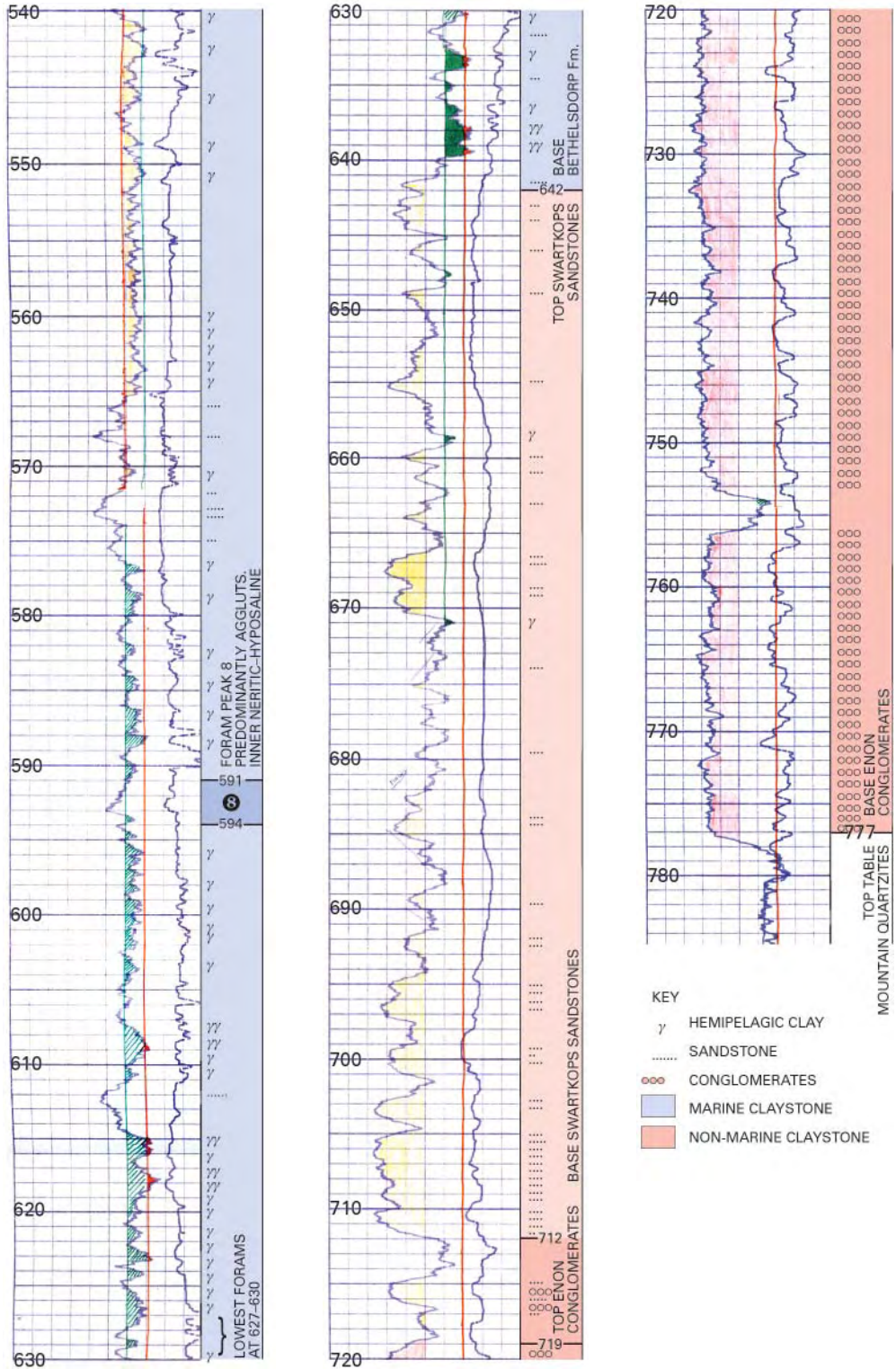
In the lower half of the Bethelsdorp Formation there are bursts of distinctly small-sized *Epistomina parastelligera* (Hofker). These abundance peaks clearly reflect a persistently shallow marine but rather dysoxic environment, in which colloidal organic matter (but not plant debris) was not being degraded rapidly enough, leading to the genesis of hydrogen sulphide and facilitating the localised formation of pyrite. These episodes perhaps reflect occasional periods of poor water circulation within the subsiding Uitenhage Trough due to fluctuating movement on the bounding Coega–St Croix fault system. These bursts of aragonitic-walled tests appear to be comparable to the *Epistomina*-dominated foraminifera assemblages

FIGURE 19 (pages 55–57)

Gamma ray log and caliper log for the graben fill succession in type section borehole BT 1/74. Depths in metres. Correlated with peaks of foraminiferal abundance.







encountered in the Late Valanginian Biozone B of the Sundays River Formation (McMillan, 2003a), but they are not as long-lived, nor as areally extensive.

Only at the base of the Bethelsdorp Formation do diverse foraminifera assemblages occur which clearly reflect normal marine, open-sea, well-oxygenated inner neritic conditions. Here occur diverse assemblages composed of agglutinated species (*Ammobaculites*, *Haplophragmoides*), nodosarids (*Astacolus*, *Dentalina*, *Lenticulina*, *Tristix*, *Fronicularia*, *Lingulina*), polymorphinids (*Eoguttulina*, *Globulina*), and aragonitic forms (*Epistomina*, *Conorboides*). Here too occur *Inoceramus* prisms and holothurian sclerites, echinoid spines and ophiuroid ossicles. As noted previously, the stratigraphic distribution of these assemblages indicate that the Bethelsdorp Formation accumulated with a slight overall shallowing-upward motif. A comparison between the Bethelsdorp foraminifera assemblages, and the foraminiferal associations and their interpreted depositional environments of the English Jurassic succession (Gordon, 1970) is of interest.

Age of the Bethelsdorp Formation

Early studies in the onshore Uitenhage Trough mostly failed to distinguish the fossil assemblage of the Bethelsdorp Formation from that of the Sundays River Formation. It has only been as a result of the deep drilling during the 20th century that the two formations could be seen to be entirely different rock units. The Bethelsdorp Formation succession intersected by borehole SW 1/08 was interpreted to be Wealden in age by Kitchin (in Rogers, 1910), whereas Rigassi & Dixon (1972), McLachlan & McMillan (1976) and McLachlan *et al.* (1976a) regarded a Berriasian to Early Valanginian age more likely. On the basis of the foraminifera taxonomy presented herein, McLachlan & McMillan (1979) emphasised the Jurassic nature of a number of the foraminifera species, and consequently suggested a Portlandian age for the Bethelsdorp Formation.

The benthic foraminifera described in the present work from the Bethelsdorp Formation of the onshore Uitenhage Trough include a number of species that have definite Jurassic associations. Nonetheless there are a considerable number of other species that are either new, or not clearly age-diagnostic, such as some of the agglutinated benthic foraminifera. There are no planktic foraminifera or radiolaria in any of the studied samples from the Bethelsdorp Formation. The benthic foraminifera assemblage of the Bethelsdorp Formation is completely different from that of the Sundays River Formation. This may well indicate that the ages of the two rock units are distinctly different, but there are also clear differences in their environments of deposition, which may have caused a biased dissimilarity. However, the absence of typical Sundays River Formation species such as *Epistomina caracolla* (Roemer) *s.l.*, *Lenticulina nodosa* (Reuss), *Astacolus gibber* Espitalié & Sigal, *Dorothia australis* McMillan, *Reinholdella valendisensis* (Bartenstein & Brand) and *Reinholdella hofkeri* (Bartenstein & Brand) in the Bethelsdorp Formation, all typically

Valanginian and ranging to variable extents into and through the Berriasian in the fully marine successions in the offshore Algoa, Gamtoos and Pletmos Basins, show that the Bethelsdorp Formation pre-dates the Berriasian.

Although it is not possible to confirm a Portlandian (topmost Jurassic) age for the Bethelsdorp Formation, for reasons detailed below, this is the preferred age for this rock unit. Comparatively few publications are available on the foraminifera of the Portlandian stage, or the partly coeval Volgian stage, around the world. In particular, the general similarity of Valanginian–Hauterivian benthic foraminiferal assemblages from Patagonia (Santa Cruz, Chubut and Neuquén) in southern Argentina, and those of the Sundays River Formation (see McMillan, 2003a, p. 22–25 for details), is not seen in the latest Jurassic rock succession. Indeed, because of differences in sedimentary facies, it has proven difficult to even correlate between the latest Jurassic benthic foraminiferal assemblages of the offshore Uitenhage Trough and the offshore Port Elizabeth Trough, both part of the Algoa Basin, as well as between the coeval deposits in the offshore Gamtoos, Pletmos and Bredasdorp Basins. The strongly facies-controlled benthic foraminifera species are often limited to one particular graben infill, as a result of the localised accumulation of estuarine claystones, littoral sandstones, inner neritic sandstones and claystones, or upper bathyal dysoxic black, organic-rich claystones. Consequently, there is no foraminiferal biostratigraphic correlation yet possible for the Late Jurassic between the various southern Gondwana continental plates, especially between southern Argentina–Chile (Ballent, 1987; Ballent *et al.*, 2006; Musacchio, 1978a, b, 1979, 1981; Dellape *et al.*, 1978; Simeoni, 2000), Antarctica, South Africa and Tanzania (Singano & Karega, 2000) Madagascar (Espitalié & Sigal, 1963a, b), India (Bhalla & Abbas, 1978), New Zealand (Hornibrook, 1953), or the Perth Basin in Australia (Chapman, 1904). There is no clear similarity with the Callovian foraminifera described from southern Argentina by Musacchio (1978a, b, 1979, 1981) and Dellape *et al.* (1978), or the Early Jurassic of Argentina (Ballent, 1987). Even with the Valanginian–Hauterivian Agrio Formation there are marked differences, such as the presence of several horizons of ornate *Epistomina*, together with *Hergottella* (Simeoni, 2000; Ballent *et al.*, 2006), features not found in the Sundays River Formation. Similar differences exist in the Austral Basin (Natland *et al.*, 1974; Malumián & Masiuk, 1975; Kielbowicz *et al.*, 1983).

Singano & Karega (2000) detailed the biostratigraphy of the Late Jurassic foraminifera of the Mandawa anticline in southern Tanzania. The Tanzanian succession appears to be characterised by small, simple agglutinated foraminifera, nodosarids (especially a variety of *Lenticulina* species), and several smooth-walled and ornamented *Epistomina* species. No larger foraminifera have been noted. It has not yet proven possible to effectively correlate the Tanzanian and South African Late Jurassic successions using foraminifera.

Foraminiferal correlation consequently can only be achieved with the European Jurassic successions, but such a correlation is especially hindered by the absence of detailed foraminiferal analysis across the type Portlandian in England. The rocks of the English Oxfordian and Kimmeridgian stages have been intensively studied for foraminifera, principally because both consist predominantly of black or grey claystones, and well-preserved foraminifera tests are easy to extract. In contrast the type Portlandian stage succession is comprised of inner neritic limestones and sandstones, which have undergone considerable calcite cementation or leaching, and there has been no comprehensive study of its foraminifera. Furthermore, the overlying Purbeck Limestones and Weald Clay are almost exclusively non-marine units. Relevant publications are few (Shipp & Murray, 1981; Shipp, 1989; Radley, 1990, 1993a,b; Radley *et al.*, 1997), and few species have been illustrated. Consequently, the relatively well-studied succession in England is of only slight help in understanding how typical Late Jurassic foraminiferal assemblages evolved into Early Cretaceous ones, and when changes occurred. Many of the datable foraminifera in the Bethelsdorp Formation are the same as or similar to species described from the relatively dysoxic facies of the Oxfordian, or the severely dysoxic facies of the Kimmeridgian of England or north-west Europe, but these species' full later stratigraphic ranges are probably obscured by the subsequent highly oxygenated, adversely fossiliferous, carbonate-rich lithofacies that prevailed in England during Portlandian time.

Foraminiferal Biozonation of the Bethelsdorp Formation

The difficulty of correlating between the mostly mud-flat sediments of the Bethelsdorp Formation of the onshore Uitenhage Trough, the lacustrine sediments of the Colchester Formation of the onshore Sundays River Trough, and the innermost neritic shelfal sediments in the coeval marine episode in the basal part of Pletmos Basin borehole PB-A1, is not experienced when correlating between the three deep boreholes and one outcrop of the onshore Uitenhage Trough. Despite the great differences in sampling frequency down the three boreholes and the Bethelsdorp Salt Pan outcrops, a detailed foraminiferal biostratigraphic correlation has been achieved. Eight foraminiferal abundance peaks can be recognised in the long borehole sections, which can be distinguished on their assemblage peculiarities. The Bethelsdorp outcrop samples can be correlated into this zonation scheme. Some of these eight abundance peaks reflect episodes of minor marine advance (especially in the lower Bethelsdorp Formation), while others reflect marked changes in depositional environment, for example rapid change from hypersaline mudflat to hypersaline estuarine channel and back to hypersaline mudflat (upper Bethelsdorp Formation). The minor marine advances probably correspond to periods of increased rate of subsidence of the Uitenhage Trough, versus a relatively steady rate of sediment input, permitting the development of short episodes of slightly greater sea-floor accommodation space. The abundance peaks are seen best in borehole BT 1/74 because of the generally clean condition of the cuttings samples in that hole. In the

more caved ST 1/71 succession the lows with rare foraminifera, in particular, are not so well defined. The more irregular scatter of samples, and the small sample size in borehole SW 1/08 has led to even more ill-defined peaks, but they are recognisable nonetheless. The lowest peak, designated number 8, contains the most diverse benthic foraminiferal assemblage, typical of inner neritic environments, with the greatest number of calcareous benthics. This peak compares best with the assemblage seen in some of the foraminifera-bearing samples from Bethelsdorp Salt Pan, especially sample numbers 11475, 11476 and 11477. From this, it is clear that the Bethelsdorp Formation shallows very gently up section, notwithstanding the eight abundance peaks. The ostracod peaks of non marine *Cypridea* and inner neritic *Progonocythere* (unpublished work by Valicenti) do not correlate with the foraminiferal abundance peaks. Examination of the outcrop sections at Bethelsdorp Salt Pan and North End Lake suggests there to be interbedded green marine clays and red fluvial clays (Stow, 1871; McLachlan & McMillan 1976).

PEAK 1

This is evident in the BT 1/74 borehole section between 258 and 270m, and is marked by the first downhole occurrence of foraminifera, and abundance peak of *Quinqueloculina grisbrooki*, and the rare occurrence of ?*Orthovertella* sp. An equivalent to Peak 1 can also be recognised in borehole ST 1/71 between 1090 and 1095m, again on the basis of ?*Orthovertella* sp., but it cannot be identified in the SW 1/08 section. This predominance of one miliolid species (with the scattered occurrence of non-marine ostracods of the genus *Cypridea*) suggests a hypersaline mud-flat environment, probably caused by wind-induced evaporation of sea-water films.

PEAK 2

This is evident in BT 1/74 borehole section from 294 to 306m, and is distinguished by an abundant peak of *Quinqueloculina grisbrooki*; it can be recognised from 1130 to 1145m in borehole ST 1/71, but cannot be identified in SW 1/08. The environment is interpreted to be much the same as that of Peak 1.

PEAK 3

Evident in BT 1/74 at 339 to 342m, distinguished by numbers of *Miliammina* and *Ammomarginulina* tests. This assemblage obviously reflects hyposaline, probably fluvial channel environments ranging across the hypersaline salt-marsh tops. The same event can be seen in ST 1/71 from 1175 to 1180m, and is probably also present in the SW 1/08 section at 2140 feet.

PEAK 4

Evident in BT 1/74 at 420 to 423m, this is indicated by a marked increase and first appearance of polymorphinids (*Eoguttulina* and *Globulina* species). It is difficult to identify this peak clearly in borehole ST 1/71, it may be at 1250 to 1255m; it cannot be recognised in the SW 1/08 section. The increasing abundance of *Eoguttulina*

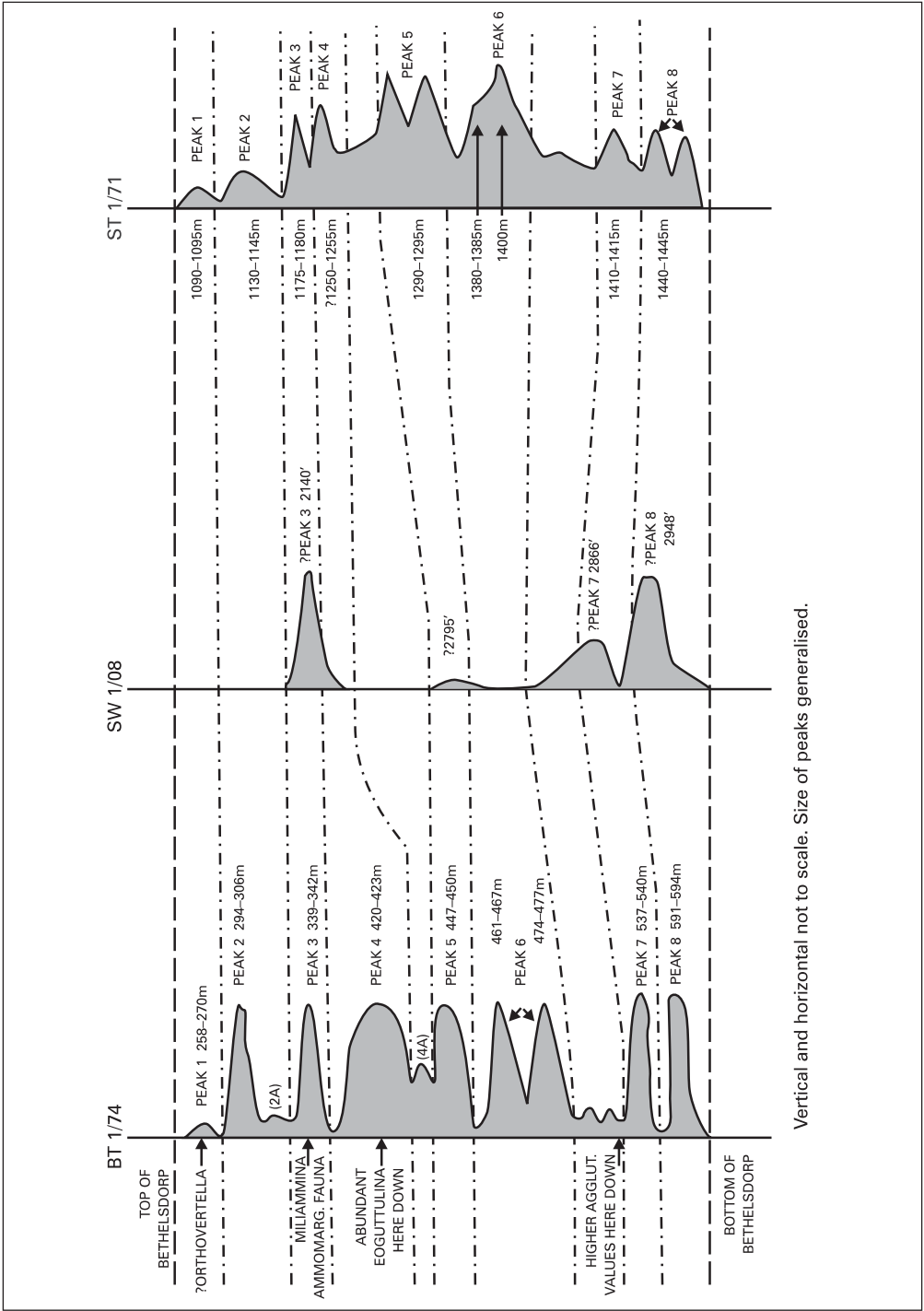


FIGURE 20

Foraminiferal abundance peaks and interpreted correlation between the three deep boreholes drilled in the onshore Uitenhage Trough

species in particular suggests rather more dysoxic conditions as a result of more organic detritus, and perhaps greater depths of permanent standing water, reflecting more nearly normal marine (not hypersaline) water conditions.

PEAKS 5 AND 6

Three peaks (6 is considered doubled into two peaks) in BT 1/74 all marked by increasing numbers of polymorphinids and agglutinated species, at 447 to 450m, 462 to 467m, and 474 to 477m. By now only occasional samples are rich in *Quinqueloculina grisbrooki*. There is a clear trend towards increasing diversity of assemblages, though somewhat erratic, and genera such as *Nodosaria*, *Tristix* and *Epistomina* occur in small numbers. The corresponding peaks in ST 1/71 are at 1290 to 1295m, 1380 to 1385m, and at 1400m: the same increasing diversity of assemblages can be recognised in this borehole section too. A small peak at 2795 feet in SW 1/08 may be Peak 5.

PEAK 7

At 537 to 540m in BT 1/74, this peak is marked by a substantial predominance of agglutinated benthic species (*Haplophragmoides* and *Ammobaculites* spp.), and very few of any calcareous genera. This suggests innermost neritic, normally oxygenated marine, but distinctly hyposaline conditions. The comparable peak in ST 1/71 is at 1410 to 1415m, but it includes more miliolids than at BT 1/74. This peak can also possibly be recognised in borehole SW 1/08 at 2866 feet.

PEAK 8

This is marked by the greatest diversity of benthic foraminifera in the entire succession, and the varied but small calcareous benthic assemblages from the Bethelsdorp Salt Pan outcrops should be allocated to Peak 8. The large-sized agglutinated benthic species *Ammobaculites subaequalis* is a diagnostic indicator in all three borehole sections and the salt pan outcrop, and emphasises the inner neritic, probably almost normal marine, wave influenced and relatively well oxygenated sea-floor conditions that prevailed at this time. This lowest peak can be recognised in BT 1/74 at 591 to 594m, in ST 1/71 at 1440 to 1445m, and in SW 1/08 at 2948 feet. Indeed, the last-named sample is distinguished by 46 benthic foraminifera species, many of which are calcareous shelled, a record for the Bethelsdorp Formation. Below this depth, benthic foraminifera fade rapidly away, and are absent in the immediately underlying Swartkops Sandstone and Enon conglomerate.

The three deep boreholes of the onshore Uitenhage Trough are the only three in which a distinct shallowing-upwards motif is evident from the benthic foraminifera assemblages. Offshore boreholes in the Uitenhage Trough, with the typically *Lenticulina*-dominated assemblages of the Bethelsdorp Formation, appear to show depositional environments are vertically stacked. In contrast, the overlying Infanta and Kirkwood Formations have a strong shallowing up motif.

TAXONOMIC LIST OF SPECIES RECOGNISED IN THIS PUBLICATION

| Species | Page | Figure drawings | Figure sem photos |
|--|------|---------------------|---------------------------------------|
| <i>Glomospira gordialis</i> (Jones & Parker) | 67 | Fig. 21, no. 1 | none |
| <i>Miliammina buchenroderi</i> n.sp. | 70 | Fig. 21, nos 2–4 | Fig. 24, nos 1–3. |
| <i>Miliammina electra</i> n.sp. | 71 | Fig. 21, nos 5–7. | Fig. 24, nos 4–7. |
| <i>Miliammina jurassica</i> (Hacuser) | 72 | Fig. 21, nos 8–10. | none |
| <i>Miliammina palustris</i> n.sp. | 73 | Fig. 21, nos 11–13. | Fig. 24, nos 8–11. |
| <i>Reophax</i> spp. | 74 | Fig. 21, no. 14. | none |
| <i>Haplophragmoides</i> sp. 1 | 75 | Fig. 21, nos 15–16. | Fig. 24, nos 12–13. |
| <i>Haplophragmoides haeusleri</i> Lloyd | 76 | Fig. 21, nos 17–18. | Fig. 24, nos 14–16. |
| <i>Haplophragmoides</i> sp. 3 | 76 | Fig. 21, nos 19–20. | Fig. 24, nos 17–18. |
| <i>Haplophragmoides</i> sp. 4 | 76 | Fig. 22, nos 1–4. | none |
| <i>Haplophragmoides</i> sp. 5 | 77 | Fig. 22, nos 5–6. | none |
| <i>Haplophragmoides</i> sp. 6 | 77 | Fig. 22, nos 7–8. | none |
| <i>Haplophragmoides</i> sp. 7 | 77 | Fig. 22, nos 9–10. | none |
| <i>Haplophragmoides</i> spp. | 79 | none | none |
| <i>Ammobaculites</i> sp. 1 | 80 | Fig. 22, nos 11–12. | Fig. 24, no. 19. |
| <i>Ammobaculites</i> sp. 2 | 80 | Fig. 22, nos 13–14. | Fig. 24, no. 20, Fig. 25, nos 1–2. |
| <i>Ammobaculites</i> sp. 3 | 81 | Fig. 22, nos 15–16. | none |
| <i>Ammobaculites</i> sp. 4 | 81 | Fig. 22, nos 17–18. | none |
| <i>Ammobaculites coprolithiformis</i> (Schwager) | 81 | Fig. 22, nos 19–20. | none |
| <i>Ammobaculites subaequalis</i> Mjatluk | 82 | Fig. 23, nos 1–2. | none |
| <i>Ammobaculites</i> spp. | 83 | none | none |
| <i>Ammomarginulina missionensis</i> n.sp. | 83 | Fig. 23, nos 3–4. | Fig. 25, nos 3–7. |
| <i>Plectinella aegyptiaca</i> (Said & Barakat) | 88 | Fig. 23, nos 5–6. | none |
| <i>Ammoglobigerina</i> cf. <i>A.globigeriniformis</i> (Parker & Jones) | 88 | Fig. 23, nos 7–9. | none |
| <i>Trochammina</i> cf. <i>T. inflata</i> (Montagu) | 90 | Fig. 23, nos 10–12. | none |
| <i>Trochammina</i> cf. <i>T. squamata</i> Jones & Parker | 90 | Fig. 23, nos 13–15. | none |
| <i>Trochammina</i> spp. | 91 | none | none |
| <i>Dorothia</i> sp. | 91 | Fig. 23, nos 16–17. | none |
| <i>Bigenerina</i> sp. | 92 | Fig. 23, nos 18–19. | none |

| | | | |
|---|-----|------------------|--|
| <i>Cornuspira orbicula</i> (Terquem & Berthelin) | 92 | none | Fig. 25, nos 8–9. |
| ‡ <i>Orthovertella</i> sp. | 93 | none | Fig. 25, no. 10. |
| <i>Nubecularia lucifuga</i> Defrance | 95 | none | Fig. 25, nos 11–12. |
| <i>Quinqueloculina grisbrooki</i> n.sp. | 96 | none | Fig. 25, nos 13–20; Fig. 26, nos 1–6. |
| <i>Sigmoilina</i> sp. | 99 | none | Fig. 26, no. 7. |
| <i>Lingulonodosaria nodosaria</i> (Reuss) | 101 | none | Fig. 26, no. 8. |
| <i>Laevidentalina communis</i> (d'Orbigny) | 102 | none | Fig. 26, no. 9–10. |
| <i>Laevidentalina</i> spp. | 103 | none | none |
| <i>Pyramidulina</i> cf. <i>P. kuhni</i> (Franke) | 103 | none | Fig. 26, nos 11–12. |
| <i>Pyramidulina minuta</i> (Cordey) | 104 | none | Fig. 26, no. 13–14. |
| <i>Pyramidulina</i> cf. <i>P. minuta</i> (Cordey) | 105 | none | Fig. 26, no. 15. |
| <i>Pyramidulina</i> sp. 1 | 105 | none | Fig. 26, no. 16. |
| <i>Nodosaria sowerbyi</i> Schwager | 106 | none | Fig. 26, nos 17–18. |
| <i>Nodosaria</i> cf. <i>N. metensis</i> Terquem | 106 | none | Fig. 26, nos 19–20. |
| <i>Lingulina dentaliniformis</i> Terquem | 109 | none | Fig. 27, nos 1–2 |
| <i>Lingulina lamellata</i> Tappan | 110 | none | Fig. 27, no. 3. |
| <i>Lingulina lanceolata</i> (Haeusler) | 111 | none | Fig. 27, nos 4–5. |
| <i>Lingulina</i> spp. | 111 | none | Fig. 27, nos 6–7. |
| <i>Fronicularia franconica</i> Gümbel | 113 | none | Fig. 27, no. 8. |
| <i>Fronicularia</i> sp. | 114 | none | Fig. 27, no. 9. |
| <i>Tristix acutangula</i> (Reuss) | 115 | none | none |
| <i>Tristix oolithica</i> (Terquem) | 115 | none | Fig. 27, nos 10–11. |
| <i>Tristix</i> sp. 1 | 116 | none | Fig. 27, nos 12–13. |
| <i>Lenticulina muensteri</i> (Roemer) | 117 | none | none |
| <i>Lenticulina</i> cf. <i>L. quenstedti</i> (Gümbel) forma A Wernli | 117 | Fig. 23, no. 20. | none |
| <i>Neoflabellina</i> sp. | 118 | none | none |
| <i>Astacolus</i> cf. <i>A. major</i> (Bornemann) forma A Lutze | 119 | none | Fig. 27, no. 14. |
| <i>Astacolus pellucida</i> Said & Barakat | 119 | none | Fig. 27, no. 15. |
| <i>Astacolus</i> sp. | 120 | none | Fig. 27, no. 16. |
| <i>Marginulina declivis</i> (Schwager) | 120 | none | Fig. 27, nos 17–18. |
| <i>Marginulina</i> spp. | 121 | none | none |
| <i>Vaginulinopsis</i> spp. | 121 | none | Fig. 27, nos 19–20. |
| <i>Citharina harpa</i> (Roemer) | 121 | none | Fig. 28, no. 1. |
| <i>Citharina inconstans</i> (Terquem) | 124 | none | Fig. 28, nos 2–3. |
| <i>Citharina</i> sp. | 124 | none | Fig. 28, no. 4. |
| <i>Planularia beierana</i> (Gümbel) | 125 | none | Fig. 28, nos 5–6. |
| <i>Planularia madagascariensis</i> Espitalié & Sigal | 126 | none | Fig. 28, nos 7–8. |
| <i>Planularia</i> spp. | 127 | none | Fig. 28, nos 9–10. |
| <i>Vaginulina</i> cf. <i>V. anomala</i> Blake | 127 | none | Fig. 28, no. 11. |

| | | | |
|--|-----|---------|--|
| <i>Vaginulina barnardi</i> Gordon | 128 | none | Fig. 28, no. 12. |
| <i>Vaginulina</i> spp. | 129 | none | none |
| <i>Lagen</i> a <i>algaensis</i> McMillan | 129 | none | Fig. 28, no. 13. |
| <i>Lagen</i> a cf. <i>L. striatifer</i> a Tappan | 130 | none | Fig. 28, no. 14. |
| <i>Lagen</i> a cf. <i>L. sulcata</i> (Walker & Jacob) | 130 | none | Fig. 28, no. 15. |
| <i>Eoguttulina anglica</i> Cushman & Ozawa | 132 | none | Fig. 28, nos 16–18. |
| <i>Eoguttulina</i> cf. <i>E. inovroclaviensis</i> (Bielecka & Pożaryski) | 132 | none | Fig. 29, nos 2–4. |
| <i>Eoguttulina liassica</i> (Strickland) | 134 | none | Fig. 28, nos 19–20; Fig. 29, no. 1. |
| <i>Eoguttulina</i> cf. <i>E. metensis</i> (Terquem) | 134 | none | Fig. 29, no. 5. |
| <i>Eoguttulina oolithica</i> (Terquem) | 135 | none | Fig. 29, no. 6. |
| <i>Eoguttulina polygona</i> (Terquem) | 137 | none | Fig. 29, nos 7–8. |
| <i>Globulina prisca</i> (Reuss) | 138 | none | Fig. 29, nos 9–10. |
| <i>Pyrulina</i> sp. | 139 | none | Fig. 29, no. 11. |
| <i>Bullopora laevis</i> (Sollas) | 139 | none | Fig. 29, no. 12. |
| <i>Webbinella subhemisphaerica</i> Franke | 140 | none | Fig. 29, nos 13–14. |
| <i>Ramulina fusiformis</i> Khan | 140 | none | Fig. 29, no. 15. |
| <i>Fissurina</i> sp. | 141 | none | Fig. 29, no. 16. |
| <i>Spirillina tenuissima</i> Gümbel | 142 | none | Fig. 29, nos 17–18. |
| <i>Turrispirillina conoidea</i> (Paalzow) | 143 | none | Fig. 29, nos 19–20. |
| <i>Patellina oolithica</i> Terquem | 143 | none | Fig. 30, no. 1. |
| <i>Reinholdella costifera</i> (Terquem) | 144 | none | Fig. 30, nos 2–5. |
| <i>Epistomina parastelligera</i> (Hofker) | 145 | none | Fig. 30, nos 6–13. |
| <i>Conorboides mariscus</i> n.sp. | 148 | none | Fig. 30, nos 14–18. |
| <i>Conorboides nudus</i> (Terquem) | 150 | none | Fig. 30, no. 19–20; Fig. 31, nos 1. |
| ? <i>Ellipsoidella</i> sp. | 151 | none | Fig. 31, no. 2. |
| Holothurian sclerite: <i>Achistrum</i> sp. | 155 | Fig. 32 | none |
| Fish otoliths (sacculiths) | 157 | none | Fig. 33, nos 1–2. |

FORAMINIFERA TAXONOMY

The taxonomy of the Bethelsdorp Formation foraminifera is based on that of Loeblich & Tappan (1988), but earlier works (Loeblich & Tappan, 1961, 1964, 1974, 1986) have also been consulted in the course of this study. The taxonomy is only taken up to family level.

Most illustrated and described specimens, including holotypes, paratypes and comparative material, have been deposited in the collections of the Iziko South African Museum in Cape Town. Each individual specimen has been allocated a catalogue number, prefixed SAM-PQ-MF, numbered from 2134 to 2307, and which is indicated in the explanations to figures. The original assemblage slides remain in the microfossil slide collection of the Petroleum Agency of South Africa in Parow, Cape Town. However, many species of foraminifera in the Bethelsdorp Formation are presently represented by only one or two specimens, so that re-examination of the assemblage slides may not yield further specimens of rare species without further picking of washed residues. This rarity is a particularly distinctive feature of the Bethelsdorp Formation foraminifera assemblages not seen in those of the Sundays River Formation.

Family AMMODISCIDAE Reuss, 1862
Subfamily AMMOVERTELLININAE Saidova, 1981
Genus GLOMOSPIRA Rzehak, 1885

Glomospira gordialis (Jones & Parker, 1860)
Fig. 21, no. 1.

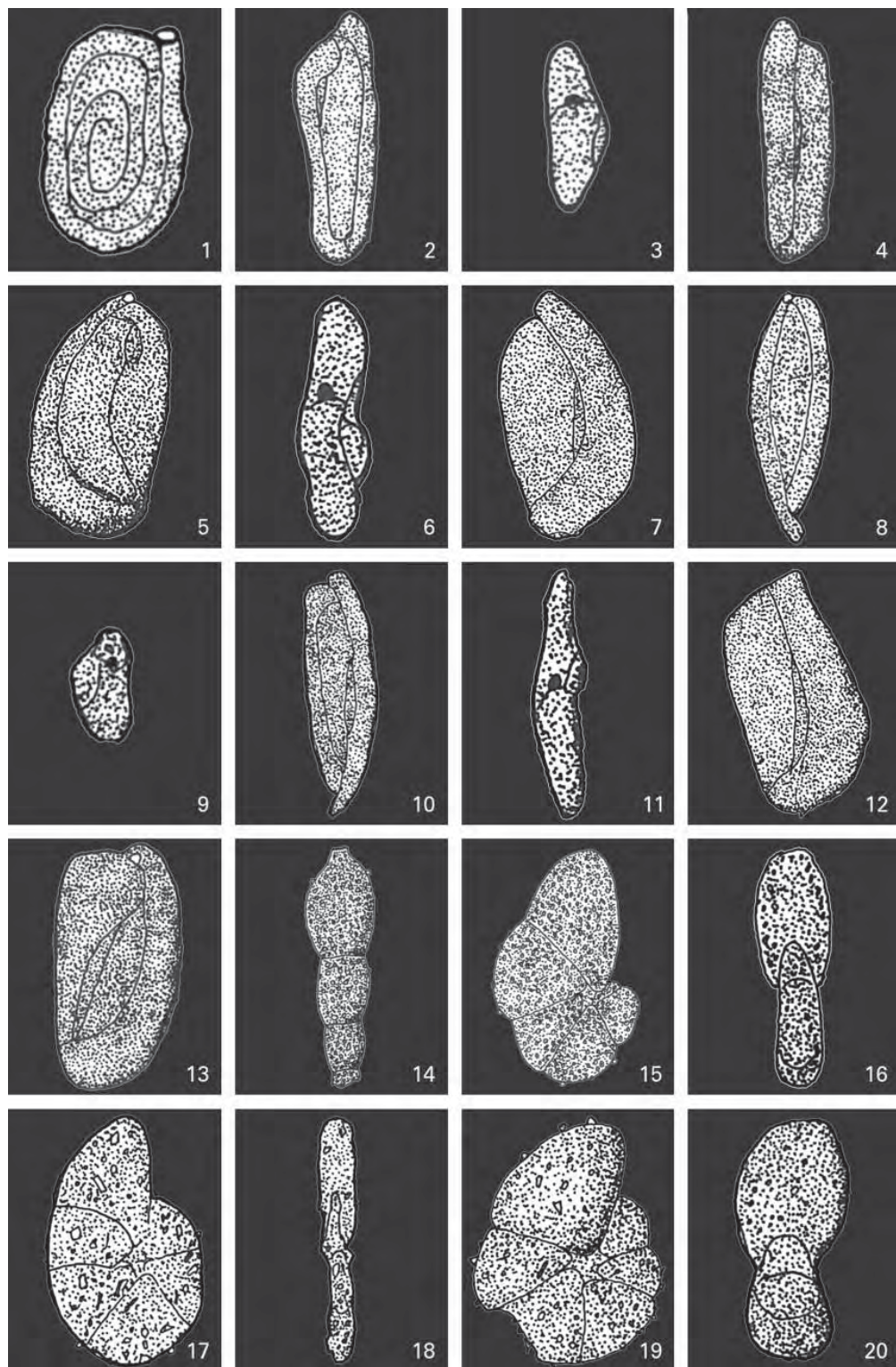
Trochammina squamata Jones & Parker *gordialis* Jones & Parker, 1860a: 304.

Glomospira gordialis (Jones & Parker); Bartenstein & Brand, 1951: 267, pl. 1, fig. 15–16; Bielecka, 1960a: 38, 114, pl. 1, fig. 2–3.

See *Glomospira gordialis* (Jones & Parker); Loeblich & Tappan, 1988: 50, pl. 38, fig. 5–6.

REMARKS

A single, fairly poorly preserved specimen of *Glomospira gordialis* was found in the topmost Bethelsdorp Formation. The test is an irregularly coiled agglutinated tube



with the test wall composed of extremely fine rather angular quartz grains. In its manner of growth it compares relatively well with illustrations and descriptions given by other authors. However, present day tests usually display a predominance of cement in the test wall (Cushman, 1918; Loeblich & Tappan, 1988), whereas our, and other, Mesozoic examples are sparsely cemented, with the quartz grains clearly evident. This species was first described from the present day Mediterranean Sea (Jones & Parker, 1860a), but the name has been widely used for fossil tests as old as the Jurassic.

OCCURRENCE IN THE BETHELSDORP FORMATION

Peak 2, topmost Bethelsdorp Formation, borehole BT 1/74, sample 303–306m.

FIGURE 21 (*facing page*)

1. *Glomospira gordialis* (Jones & Parker). SAM-PQ-MF-2189. BT 1/74, 303–306m. Side view. $\times 248$. **2–4.** *Miliammina buchenroderi* n. sp. McMillan. Holotype. **2.** SAM-PQ-MF-2190. BT 1/74, 339–342m. Side view. $\times 188$. **3.** SAM-PQ-MF-2190. BT 1/74, 339–342m. Apertural view (same specimen as No. 2). $\times 126$. **4.** SAM-PQ-MF-2190. BT 1/74, 339–342m. Opposite side view (same specimen as No. 2). $\times 182$. **5–7.** *Miliammina electra* n. sp. McMillan. Holotype. **5.** SAM-PQ-MF-2194. BT 1/74, 339–342m. Side view. $\times 213$. **6.** SAM-PQ-MF-2194. BT 1/74, 339–342m. Apertural view (same specimen as No. 5). $\times 220$. **7.** SAM-PQ-MF-2194. BT 1/74, 339–342m. Opposite side view (same specimen as No. 5). $\times 226$. **8–10.** *Miliammina jurassica* (Haeusler). **8.** SAM-PQ-MF-2199. SW1/08, 2948'. Side view. $\times 226$. **9.** SAM-PQ-MF-2199. SW1/08, 2948'. Apertural view (same specimen as No. 8). $\times 229$. **10.** SAM-PQ-MF-2199. SW1/08, 2948'. Opposite side view (same specimen as No. 8). $\times 213$. **11–13.** *Miliammina palustris* n. sp. McMillan. Holotype. **11.** SAM-PQ-MF-2200. BT 1/74, 339–342m. Apertural view. $\times 197$. **12.** SAM-PQ-MF-2200. BT 1/74, 339–342m. Side view (same specimen as No. 11). $\times 197$. **13.** SAM-PQ-MF-2200. BT 1/74, 339–342m. Opposite side view (same specimen as No. 11). $\times 203$. **14.** *Reophax* sp. SAM-PQ-MF-2205. BT 1/74, 348–351. Side view. $\times 170$. **15–16.** *Haplophragmoides* sp.1. **15.** SAM-PQ-MF-2206. BT 1/74, 258–261m. Side view. $\times 128$. **16.** SAM-PQ-MF-2206. BT 1/74, 258–261m. Apertural view (same specimen as No. 15). $\times 132$. **17–18.** *Haplophragmoides haeusleri* Lloyd. **17.** SAM-PQ-MF-2209. BT 1/74, 303–306m. Side view. $\times 170$. **18.** SAM-PQ-MF-2209. BT 1/74, 303–306m. Edge view (same specimen as No. 17). $\times 146$. **19–20.** *Haplophragmoides* sp. 3. **19.** SAM-PQ-MF-2213. BT 1/74, 420–423m. Side view. $\times 94$. **20.** SAM-PQ-MF-2213. BT 1/74, 420–423m. Edge view (same specimen as No. 19). $\times 101$.

Family RZEHAKINIDAE Cushman, 1933
Genus MILIAMMINA Heron-Allen & Earland, 1930

Miliammina buchenroderi n. sp. McMillan

Fig. 21, nos 2–4; Fig. 24, nos 1–3.

DESCRIPTION

Test fairly small, elongate, inflated, with sides of test roughly parallel. Chambers arranged in a quinqueloculine manner. Periphery of the test broadly rounded to sub-rounded. Maximum height of test from two to three times as great as maximum width. Chambers increase fairly steadily in size as added, being from faintly to fairly strongly inflated. Sutures mostly indistinct, becoming distinct, depressed between the last-formed two or three chambers of the test. Aperture terminal, on the last-formed chamber, a broadly arched opening with a prominent apertural tooth. Surface of test smooth, composed of very fine quartz grains with little cement. Most specimens are white in colour.

VARIATION

The chambers of this species vary considerably in shape and degree of inflation, but in all of the examples studied, the basic elongate shape of the test is maintained, although the degree of test compression varies from specimen to specimen.

DERIVATIO NOMINIS

Named after early South African geologist Baron von Buchenroder.

NUMBER OF SPECIMENS

Six.

HOLOTYPE

339–342m cuttings sample, borehole BT 1/74, illustrated as Fig. 21, nos 2–4.

STRATUS TYPICUS

Borehole BT 1/74, cuttings sample 339–342m: Portlandian Bethelsdorp Formation, Uitenhage Trough, Algoa Basin.

PARATYPES

Borehole BT 1/74, cuttings sample 339–342m, illustrated as Fig. 24, nos 1–3.

REMARKS

The elongate, parallel-sided tests of *Miliammina buchenroderi* distinguish it clearly from the Valanginian *Miliammina valdensis* Bartenstein & Brand (1951) and *Miliammina latrobei* McMillan (2003a), the Portlandian *Miliammina electra* n. sp., and *Miliammina palustris* n. sp. The absence of a pronounced apertural neck, and the

irregularity of the chambers indicates it to be clearly distinct from *Miliammina olgae* Bielecka (1960a) or *Miliammina jurassica* (Haeusler, 1882).

OCCURRENCE IN THE BETHELSDORP FORMATION

339 to 465m in BT 1/74; nowhere else.

Miliammina electra n. sp. McMillan

Fig. 21, nos 5–7; Fig. 24, nos 4–7.

DESCRIPTION

Test small, inflated, with periphery of test broadly rounded, and outline of test elongate-ovate to sub-rectangular. Chambers arranged in a quinqueloculine manner. Sides of test almost parallel. Maximum height of test from $1\frac{1}{2}$ to $2\frac{1}{2}$ times as great as maximum width. Chambers increase steadily in size as added, and are strongly inflated throughout. Earlier chambers are prominent. Sutures depressed and distinct throughout. Aperture terminal, on the last-formed chamber, usually a small, low arch with no apertural tooth. Surface of test smooth, almost glassy, composed of very fine quartz grains in a small amount of cement. The colour of all the specimens examined is orange-brown.

VARIATION

The outline of the test becomes almost rectangular in some specimens, and the degree of inflation varies.

DERIVATIO NOMINIS

From *electrum* (L.), referring to the amber-like colour of the test wall, probably caused by ferric iron precipitation.

NUMBER OF SPECIMENS

Five.

HOLOTYPE

BT 1/74, cuttings sample 339–342 m, Fig. 21, nos 5–7. Bethelsdorp Formation, Portlandian, Uitenhage Trough, Algoa Basin.

STRATUS TYPICUS

Borehole BT 1/74, cuttings sample 339–342m: Portlandian Bethelsdorp Formation.

PARATYPES

BT 1/74, cuttings sample 339–342m. Four illustrated as Fig. 24, nos 4–7.

REMARKS

Miliammina electra differs from *Miliammina valdensis*, described by Bartenstein & Brand (1951) from the Wealden 6 (latest Berriasian to earliest Valanginian) of north-west Germany, in possessing more strongly inflated chambers, a smaller aperture and a more elongate, more sub-rectangular test outline. *Miliammina valdensis* also possesses an apertural neck (see Bartenstein & Brand, 1951, pl. 13, fig. 361a, b, in particular), a feature not seen in *Miliammina electra*.

Miliammina electra differs from *Miliammina jurassica*, first described by Haeusler (1882) from the Oxfordian of Switzerland, in displaying a wider, much less elongate test, and in lacking an apertural neck (see Oesterle, 1968, text-fig. 19–20). *Miliammina electra* differs from *Miliammina olgae*, described by Bielecka (1960a) from the lower Malm of southern Poland, in its inflated test, and in lacking any apertural neck. The more rectangular test outline of *Miliammina electra* distinguishes it from the rounded tests of the extant species *Miliammina fusca* (Brady), widespread in present-day upper estuarine environments.

OCCURRENCE IN THE BETHELSDORP FORMATION

258 to 469m in BT 1/74; 1175 to 1475m in ST 1/71; nowhere else.

Miliammina jurassica (Haeusler, 1882)

Fig. 21, nos 8–10.

Trochammina jurassica Haeusler, 1882: 58, pl. 4, fig. 31–40.

Miliammina jurassica (Haeusler); Seibold & Seibold, 1960: 338, pl. 7, fig. 9, text-fig. 4h–i; Oesterle, 1968: 723, fig. 19–20; Winter, 1970: 6, pl. 2, fig. 33; Morris & Coleman, 1989: 218, pl. 6.3.6, fig. 5.

REMARKS

The Bethelsdorp Formation specimens compare fairly well with earlier descriptions and illustrations of this species. The coarse-grained nature of the test wall is apparent in the South African examples, although the sponge spicules noted by Haeusler (1882) as present in the test wall were not found in our specimens. The outline of the test is similar, but the pronounced apertural neck evident in Haeusler's and Oesterle's specimens is less well developed in the South African tests. This *Miliammina* species appears to inhabit inner neritic environments in association with 45 other, mainly calcareous foraminifera species: so its environmental tolerances differ considerably from those of the other three *Miliammina* species detailed here.

The species appears to be limited to the Oxfordian and Kimmeridgian of southern Germany and Switzerland. Morris & Coleman (1989) report it from the lower Oxford Clay.

OCCURRENCE IN THE BETHELSDORP FORMATION

2948' only in SW 1/08.

Miliammina palustris n. sp. McMillan

Fig. 21, nos 11–13; Fig. 24, nos 8–11.

DESCRIPTION

Test small, strongly compressed, ovate in outline, with periphery of test rounded to sub-rounded, and greatest width of test at, or about, mid-height. Maximum height of test about $1\frac{1}{2}$ to twice the maximum width of test. Chambers arranged in a quinqueloculine manner, and are weakly inflated. The initial part of the last-formed chamber is often rather larger than the same part of earlier chambers. Chambers increase steadily in size as added. The earlier chambers do not protrude at all from the sides of the test, but lie flush with the surface of the final two chambers. Sutures distinct and faintly depressed. Aperture terminal, on the last-formed chamber: in form a broadly rounded arch with a slight lip, and there is a small short apertural tooth. The surface of the test is faintly roughened and almost glossy, and is composed of very fine grains of quartz set in very little cement.

VARIATION

The ovate outline of the test varies slightly in the specimens studied. In some tests, no apertural tooth could be seen, but it may be absent as a result of damage. On some specimens there are occasional faint depressions of the test wall: these depressions may have been caused by movement at a time of chamber construction, or they may be due to differential post-depositional compaction of the sediment surrounding the test. The strongly compressed tests of this species are very distinctive, and would appear not to have been caused by sediment compaction, as all tests are affected in exactly the same way.

DERIVATIO NOMINIS

From *paluster*, *palustris*, *palustre* (L.): marshy, indicating the interpreted environment of the species.

NUMBER OF SPECIMENS

Six.

HOLOTYPE

Cuttings sample 339–342m, borehole BT 1/74, illustrated as Fig. 21, nos 11–13.

STRATUS TYPICUS

Borehole BT 1/74, cuttings sample 258–261m: Portlandian Bethelsdorp Formation, onshore Uitenhage Trough, Algoa Basin.

PARATYPES

Cuttings sample 339–342m, borehole BT 1/74, illustrated as Fig. 24, nos 8–11.

REMARKS

Few species of the genus *Miliammina* have been described from latest Jurassic or early Cretaceous rocks, which is rather surprising considering the known extent of fluvial, hyposaline and innermost neritic environments which prevailed during this time period. *Miliammina palustris* lacks the apertural neck and the inflated, cylindrical chambers of *Miliammina valdensis*, described by Bartenstein & Brand (1951) from the topmost Wealden 6 (latest Berriasian to earliest Valanginian, according to Kemper, 1973). Said & Barakat (1958) described *Miliammina* cf. *valdensis* Bartenstein & Brand from the Kimmeridgian of Gebel Maghara, Sinai, Egypt, but their description and illustration do not indicate any similarities or differences between the Egyptian and German specimens.

Miliammina palustris differs strongly from both *Miliammina jurassica* (Haeusler) and *Miliammina olgae* Bielecka, in lacking a long, narrow, parallel-sided test, and in lacking inflated, broadly rounded chambers. The strongly compressed test of *Miliammina palustris* distinguishes it from the other new species of *Miliammina* here described from the Bethelsdorp Formation (*Miliammina electra* and *M. buchenroderi*), and from *Miliammina latrobei* McMillan (2003a), described from the Kirkwood–Sundays River transition (mid Valanginian) in the onshore Algoa Basin.

OCCURRENCE IN THE BETHELSDORP FORMATION

258 to 612m in BT 1/74; 1175–1415m in ST 1/71; 2140 to 2948' in SW 1/08; nowhere else.

Family HORMOSINIDAE Haeckel, 1894

Subfamily REOPHACINAE Cushman, 1910

Genus: REOPHAX de Montfort, 1808

Reophax spp.

Fig. 21, no. 14.

REMARKS

A few small damaged tests apparently referable to *Reophax*. Most possess test walls composed of variously sized quartz grains, giving rise to a very rough external surface, though one consists only of very fine quartz grains, resulting in a smooth, even surface. In a number of specimens the initial part of the test is missing through damage, so that the generic placement must remain in some doubt. However, the rectilinear chamber arrangement throughout, with the globular, separated chambers, tends to indicate *Reophax*, rather than the uncoiled portion of a species of *Ammobaculites*. The

rougher-surfaced forms appear similar to *Reophax horridus* (Schwager), first described from the Oxfordian of southern Germany (Schwager, 1865).

OCCURRENCE IN THE BETHELSDORP FORMATION

348 to 467.3m in BT 1/74; 2100' only in SW 1/08; nowhere else.

Family HAPLOPHRAGMOIDIDAE Maync, 1952

Genus HAPLOPHRAGMOIDES Cushman, 1910

REMARKS

The numerous specimens of *Haplophragmoides* in the Bethelsdorp Formation of the Uitenhage Trough have proven to be one of the most difficult portions of these assemblages to speciate. Partly because of test morphology, partly because of post-depositional test deformation, and partly because of often poor preservation, none of the recognised morphotypes are completely distinguishable from each other, and often there is a gradation of all test features from one species to another. As a result, the *Haplophragmoides* taxonomy given below is somewhat subjective. These species of *Haplophragmoides* show no clear similarity to those detailed by McMillan (2003a) from the Sundays River Formation.

The most important test features which have been appraised are the outline, size and shape of test, the nature and composition of the test wall, the degree of inflation of chambers, the degree of depression of the sutures, and the number of chambers in the final whorl. Features such as the shape and size of the aperture, the form of the sutures, and the degree of compression of the test, have proved of little use. Almost always the aperture is completely obscured, often the surface of agglutinated grains hides the nature of the sutures, and varying post-depositional compaction has affected the compression of the tests to a greater or lesser extent.

Haplophragmoides sp. 1

Fig. 21, nos 15–16; Fig. 24, nos 12–13.

REMARKS

Haplophragmoides species distinguished by about six chambers in the final whorl, with distinct quartz grains set in the test wall, straight or weakly curved, depressed sutures, final few chambers inflated and with lobulate test periphery, and with distinct umbilical depression.

OCCURRENCE IN THE BETHELSDORP FORMATION

258 to 558m in BT 1/74; 1100 to 1475m in ST 1/71; 2090 to 2140' in SW 1/08; not in BSP.

Haplophragmoides haeusleri Lloyd, 1959
Fig. 21, nos 17–18; Fig. 24, nos 14–16.

Haplophragmoides haeusleri Lloyd, 1959: 314, pl. 54, fig. 22, text-figs 5i–j.

REMARKS

Haplophragmoides species distinguished by about six chambers in the final whorl, test wall agglutinated fairly coarsely, test strongly compressed, and test periphery usually non-lobulate. The South African specimens compare well with Lloyd's (1959) description and illustrations of this species, but they are distinctly smaller in size. The aperture is not clearly visible on any of the many specimens from the Bethelsdorp Formation. As noted by Lloyd, the rather coarsely agglutinated material, all quartz grains, tends to obscure the line of the sutures. The final few chambers are extremely weakly inflated, and the periphery very slightly lobulate. The umbilicus is not very distinct. These tests are probably the same species as that occurring in abundance near the Kirkwood–Sundays River boundary at 3356' in fully cored borehole CO 1/67 (McMillan, 2003a, p. 12, fig. 4) in the first marine event in the Sundays River Trough.

OCCURRENCE IN THE BETHELSDORP FORMATION

303 to 630m in BT 1/74; 1090 to 1465m in ST 1/71; 2090–3023' in SW 1/08; not in BSP.

Haplophragmoides sp. 3
Fig. 21, nos 19–20; Fig. 24, nos 17–18.

REMARKS

Haplophragmoides species distinguished by large test size, strongly lobulate test periphery, with from six to seven inflated chambers in the last-formed whorl, depressed and straight, radiate sutures, distinct and depressed umbilicus.

OCCURRENCE IN THE BETHELSDORP FORMATION

420 to 621m in BT 1/74; 1260 to 1265m in ST 1/71; not in SW 1/08 or BSP.

Haplophragmoides sp. 4
Fig. 22, nos 1–4.

REMARKS

Haplophragmoides species distinguished by about eight chambers in the final whorl, large compressed test, with evenly and finely-grained test wall, shallow umbilicus and flush straight and radiate sutures.

OCCURRENCE IN THE BETHELSDORP FORMATION

420 to 467.3m in BT 1/74; 1260–1265m in ST 1/71; 2948' in SW 1/08; not in BSP.

Haplophragmoides sp. 5

Fig. 22, nos 5–6.

REMARKS

Haplophragmoides species distinguished by severely compressed test, very fine-grained quartz grains in test wall, strongly lobulate test periphery, and with five chambers in the last-formed whorl, sutures slightly curved, radiate, flush, no pronounced umbilicus. *Haplophragmoides* sp. 5 is similar to the *Haplophragmoides* tests occurring in the hyposaline claystones, considered to be Bethelsdorp Formation equivalent, in the onshore Gamtoos Basin borehole MK 1/70: see Fig. 5.

OCCURRENCE IN THE BETHELSDORP FORMATION

591 to 603m in BT 1/74; not in ST 1/71 or SW 1/08; BSP 11477.

Haplophragmoides sp. 6

Fig. 22, nos 7–8.

REMARKS

Haplophragmoides species similar to *Haplophragmoides* sp. 1, but with a distinctly coarser agglutinated test wall.

OCCURRENCE IN THE BETHELSDORP FORMATION

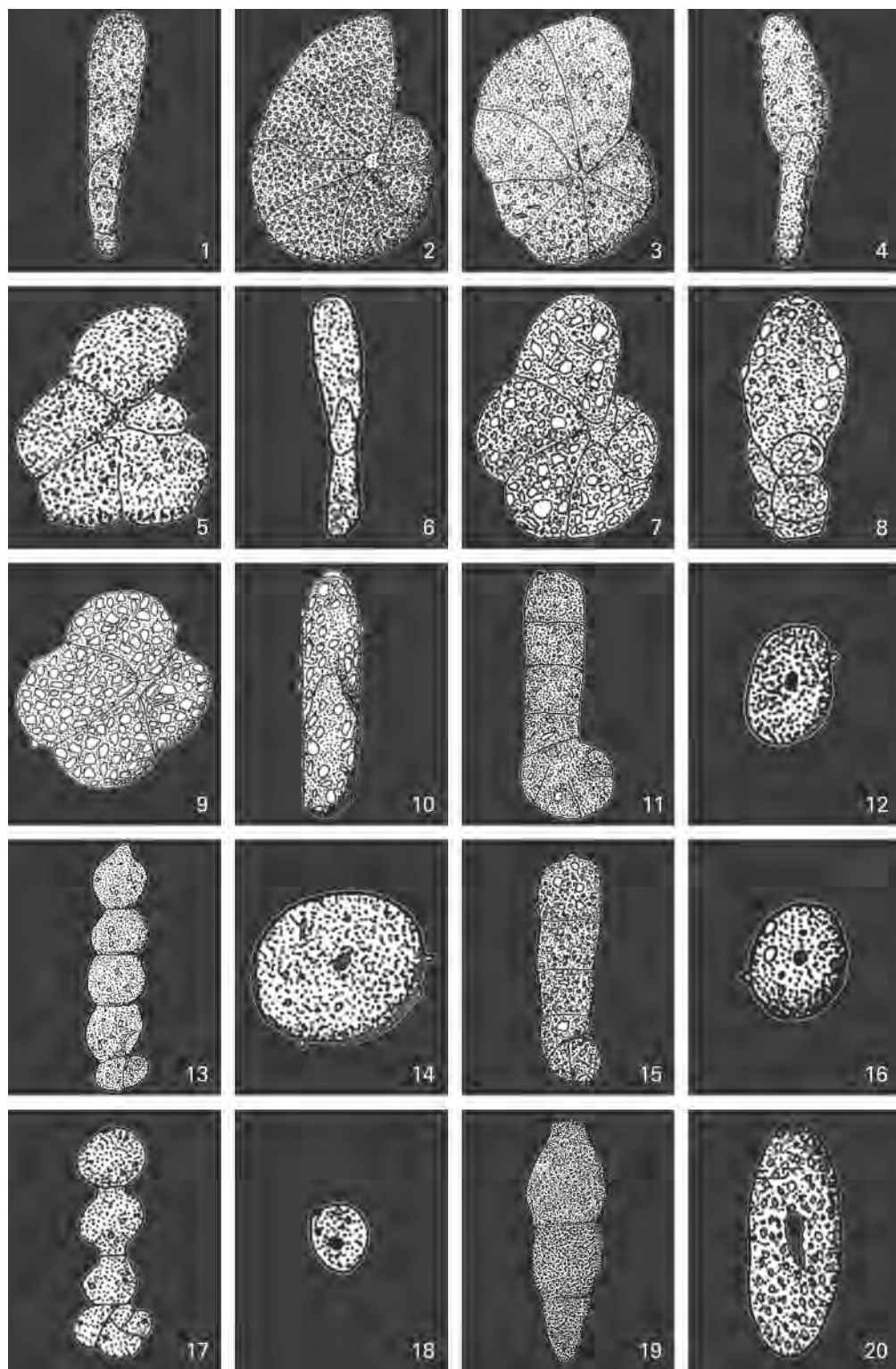
537 to 621m in BT 1/74; 1360 to 1455m in ST 1/71; 2100 to 2948' in SW 1/08; BSP 11477.

Haplophragmoides sp. 7

Fig. 22, nos 9–10.

REMARKS

Tests similar in outline and arrangement to those of *Haplophragmoides* sp. 5. This species is distinguished by rather poorly formed chamber arrangement, with flattened test due to compaction. This species occurs only in the lowest part of the Bethelsdorp Formation, which is the most nearly normal marine, inner neritic portion of the succession. *Haplophragmoides* sp. 7 tests are frequently merely agglutinated-walled flat discs, with minimum descriptive character.



OCCURRENCE IN THE BETHELSDORP FORMATION

591 to 612m in BT 1/74; not in ST 1/71, SW 1/08 or BSP.

Haplophragmoides spp.

REMARKS

Many specimens of *Haplophragmoides* were too poorly preserved, or too indistinct in their chamber form and arrangement, for them to be speciated. These various tests have been included herein.

OCCURRENCE IN THE BETHELSDORP FORMATION

258 to 630m in BT 1/74; 1110 to 1465m in ST 1/71; 2090 to 3130' in SW 1/08; not in BSP.

FIGURE 22 (*facing page*)

1–4. *Haplophragmoides* sp. 4. **1.** SAM-PQ-MF-2214. BT 1/74, 420–423m. Edge view. $\times 88$. **2.** SAM-PQ-MF-2214. BT 1/74, 420–423m. Side view (same specimen as No. 1). $\times 116$. **3.** SAM-PQ-MF-2215. BT 1/74, 420–423m. Side view. $\times 136$. **4.** SAM-PQ-MF-2215. BT 1/74, 420–423m. Edge view (same specimen as No. 3). $\times 100$. **5–6.** *Haplophragmoides* sp. 5. **5.** SAM-PQ-MF-2216. BT 1/74, 591–594m. Side view. $\times 98$. **6.** SAM-PQ-MF-2216. BT 1/74, 591–594m. Edge view (same specimen as No. 5). $\times 116$. **7–8.** *Haplophragmoides* sp. 6. **7.** SAM-PQ-MF-2217. BT 1/74, 537–540m. Side view. $\times 113$. **8.** SAM-PQ-MF-2217. BT 1/74, 537–540m. Edge view (same specimen as No. 7). $\times 123$. **9–10.** *Haplophragmoides* sp. 7. **9.** SAM-PQ-MF-2218. BT 1/74, 591–594m. Side view. $\times 135$. **10.** SAM-PQ-MF-2218. BT 1/74, 591–594m. Edge view (same specimen as No. 9). $\times 150$. **11–12.** *Ammobaculites* sp. 1. **11.** SAM-PQ-MF-2219. BT 1/74, 303–306m. Side view. $\times 71$. **12.** SAM-PQ-MF-2219. BT 1/74, 303–306m. Edge view (same specimen as No. 11). $\times 135$. **13–14.** *Ammobaculites* sp. 2. **13.** SAM-PQ-MF-2221. BT 1/74, 366–369m. Side view. $\times 87$. **14.** SAM-PQ-MF-2221. BT 1/74, 366–369m. Apertural view (same specimen as No. 13). $\times 110$. **15–16.** *Ammobaculites* sp. 3. **15.** SAM-PQ-MF-2225. BT 1/74, 467.0m. Side view. $\times 82$. **16.** SAM-PQ-MF-2225. BT 1/74, 467.0m. Apertural view (same specimen as No. 15). $\times 84$. **17–18.** *Ammobaculites* sp. 4. **17.** SAM-PQ-MF-2226. BT 1/74, 546–549m. Side view. $\times 89$. **18.** SAM-PQ-MF-2226. BT 1/74, 546–549m. Apertural view (same specimen as No. 17). $\times 82$. **19–20.** *Ammobaculites coprolithiformis* (Schwager). **19.** SAM-PQ-MF-2227. SW 1/08, 2948'. Side view. $\times 38$. **20.** SAM-PQ-MF-2227. SW 1/08, 2948'. Apertural view (same specimen as No. 19). $\times 87$.

Family LITUOLIDAE de Blainville, 1827
Subfamily AMMOMARGINULININAE Podobina, 1978
Genus AMMOBACULITES Cushman, 1910

REMARKS

Most of the remarks relevant to the genus *Haplophragmoides* apply here. The test morphologies of these *Ammobaculites* species are quite unlike those of the Sundays River Formation, as detailed by McMillan (2003a). Most of the described species as yet have no age-diagnostic significance, but *Ammobaculites coprolithiformis* (Schwager) has a clear Jurassic age-limitation. There are generally fewer numbers of *Ammobaculites* tests in most Bethelsdorp Formation foraminiferal assemblages than of *Haplophragmoides*. The presence of these two genera especially in the lower, more marine-influenced half of the Bethelsdorp Formation is taken to indicate distinctly hyposaline environments associated with a lower estuary to inner neritic setting, comparable in some degree with those of the Sundays River Formation (McMillan, 2003a).

Ammobaculites sp. 1

Fig. 22, nos 11–12; Fig. 24, no. 19.

REMARKS

This species of *Ammobaculites* is distinguished by the use of fairly coarse quartz grains for the test wall, an ovate, slightly compressed test in cross-section in the uncoiled adult portion, and the uncoiled chambers are not inflated, with the test margin continuous. There is no obvious umbilical depression, and the terminal face of the last-formed chamber is usually flat.

OCCURRENCE IN THE BETHELSDORP FORMATION

303 to 621m in BT 1/74; 1120–1465m in ST 1/71; 2100–2948' in SW 1/08; BSP 11477.

Ammobaculites sp. 2

Fig. 22, nos 13–14; Fig. 24, no. 20; Fig. 25, nos 1–2.

REMARKS

Ammobaculites sp. 2 is distinguished by several inflated, sub-globular chambers in the uncoiled portion of the test, a small umbilicus in the coiled portion, and a strongly lobate margin to the entire test. The sub-circular apertural opening is developed on a short tapering neck. The test wall is composed of a mixture of coarse and fine quartz grains. As understood herein, tests of this species can be divided into two groups: those with short adult portions composed of about three chambers (*Ammobaculites* sp. 2), and those with long adult portions composed of

about five chambers (*Ammobaculites* sp. 2A). However, it is not clear if these groups are the same or different species.

OCCURRENCE IN THE BETHELSDORP FORMATION

366 to 621m in BT 1/74; 1170 to 1455m in ST 1/71; 2100 to 2948' in SW 1/08; not in BSP.

Ammobaculites sp. 3

Fig. 22, nos 15–16.

REMARKS

Distinguished by a coarsely agglutinated, rough test wall, but otherwise similar to *Ammobaculites* sp. 1, more circular in cross-section of adult portion of test, and with a flat terminal face to the last-formed chamber.

OCCURRENCE IN THE BETHELSDORP FORMATION

467.0m to 630m in BT 1/74; 1290 to 1455m in ST 1/71; 2100 to 2866' in SW 1/08; not in BSP.

Ammobaculites sp. 4

Fig. 22, nos 17–18.

REMARKS

A small globular-chambered form, similar to *Ammobaculites* sp. 2, but much smaller in size, and with consistently small-sized quartz grains forming the test wall.

OCCURRENCE IN THE BETHELSDORP FORMATION

546 to 549m in BT 1/74; 2948' in SW 1/08; not in ST 1/71 or BSP.

Ammobaculites coprolithiformis (Schwager, 1867)

Fig. 22, nos 19–20.

Haplophragmium coprolithiformis Schwager, 1867: 654, pl. 34, fig. 3.

Ammobaculites coprolithiformis (Schwager); Bielecka & Pożaryski, 1954: 27, 161, pl. 3, fig. 6a–b; Gordon, 1961: 523, text-fig. 1, nos 8–10; Gordon, 1965: 833, text-fig. 2, text fig. 3, nos 25–28; Morris & Coleman, 1989: 218, pl. 6.3.6, fig. 2.

REMARKS

Many names have been proposed for Jurassic and Early Cretaceous larger species of *Ammobaculites*, based on variations in the size of initial coil, the number of whorls

and the number of chambers it possesses; as well as the shape and numbers of chambers in the uniserial part; and the size of the coiled and rectilinear portions relative to each other. Almost all specimens of these larger *Ammobaculites* species possess a very coarse-grained test wall. The few specimens referable to this group are limited to the basal, most marine part of the Bethelsdorp Formation. They appear to be most closely similar to *Ammobaculites coprolithiformis*, but many specimens have suffered varying degrees of post-mortem compression of the test.

Those specimens which are relatively uncompressed show the initial coil to be composed of three or four chambers in the final whorl, followed by up to four tapering chambers in the rectilinear portion of the test. The chambers of the uniserial part are distinct, inflated, and generally longer than broad, unlike the uncoiled chambers of other Jurassic–Early Cretaceous *Ammobaculites* species (such as *A. subaequalis* Mjatluk), which are generally broader than long. The tapering nature of the uncoiled portion of these tests referred to *Ammobaculites coprolithiformis* is a chamber morphology not seen at all in the Late Valanginian to Hauterivian Sundays River Formation of the Algoa Basin (McMillan, 2003a) or in the comparable Early Cretaceous beds of the southern offshore of South Africa, and is considered a Jurassic morphology.

Ammobaculites coprolithiformis was originally described by Schwager (1867) from the Bajocian (Middle Jurassic) of Württemberg. There are numerous records of it from the Late Jurassic, and it would appear to range from the Lias to the Portlandian in north-west Europe (Gordon, 1961).

OCCURRENCE IN THE BETHELSDORP FORMATION

591 to 621m in BT 1/74; 2866' and 2948' in SW 1/08; not in ST 1/71 or BSP.

Ammobaculites subaequalis Mjatluk, 1939

Fig. 23, nos 1–2.

Ammobaculites subaequalis Mjatluk, 1939: 44, pl. 2, fig. 19a–b; McMillan, 2003a: 83, figs 30A–D.

REMARKS

A few specimens of a relatively large-sized, thick-walled *Ammobaculites* occur in the more marine levels of the Bethelsdorp Formation, that are virtually identical with those found widely in the Sundays River Formation (McMillan, 2003a), and also extensively in the southern offshore Portlandian to Early Aptian succession of South Africa. Chamber morphology and sizes and arrangements of small and large quartz grains in the test wall are much the same in tests from both the Sundays River Formation (McMillan, 2003a, p. 85) and the Bethelsdorp Formation.

OCCURRENCE IN THE BETHELSDORP FORMATION

591 to 621m in BT 1/74; 1440 to 1445m in ST 1/71; 3023' in SW 1/08; BSP 11477.

Ammobaculites spp.

REMARKS

Again, as with the genus *Haplophragmoides*, there are numbers of broken, severely distorted or badly damaged or cemented tests of *Ammobaculites* species that cannot be further subdivided into particular species.

OCCURRENCE IN THE BETHELSDORP FORMATION

321 to 531m in BT 1/74; 1150 to 1445m in ST 1/71; 2100 to 2948' in SW 1/08; not in BSP.

Genus AMMOMARGINULINA Wiesner, 1931

Ammomarginulina missionensis n. sp. McMillan

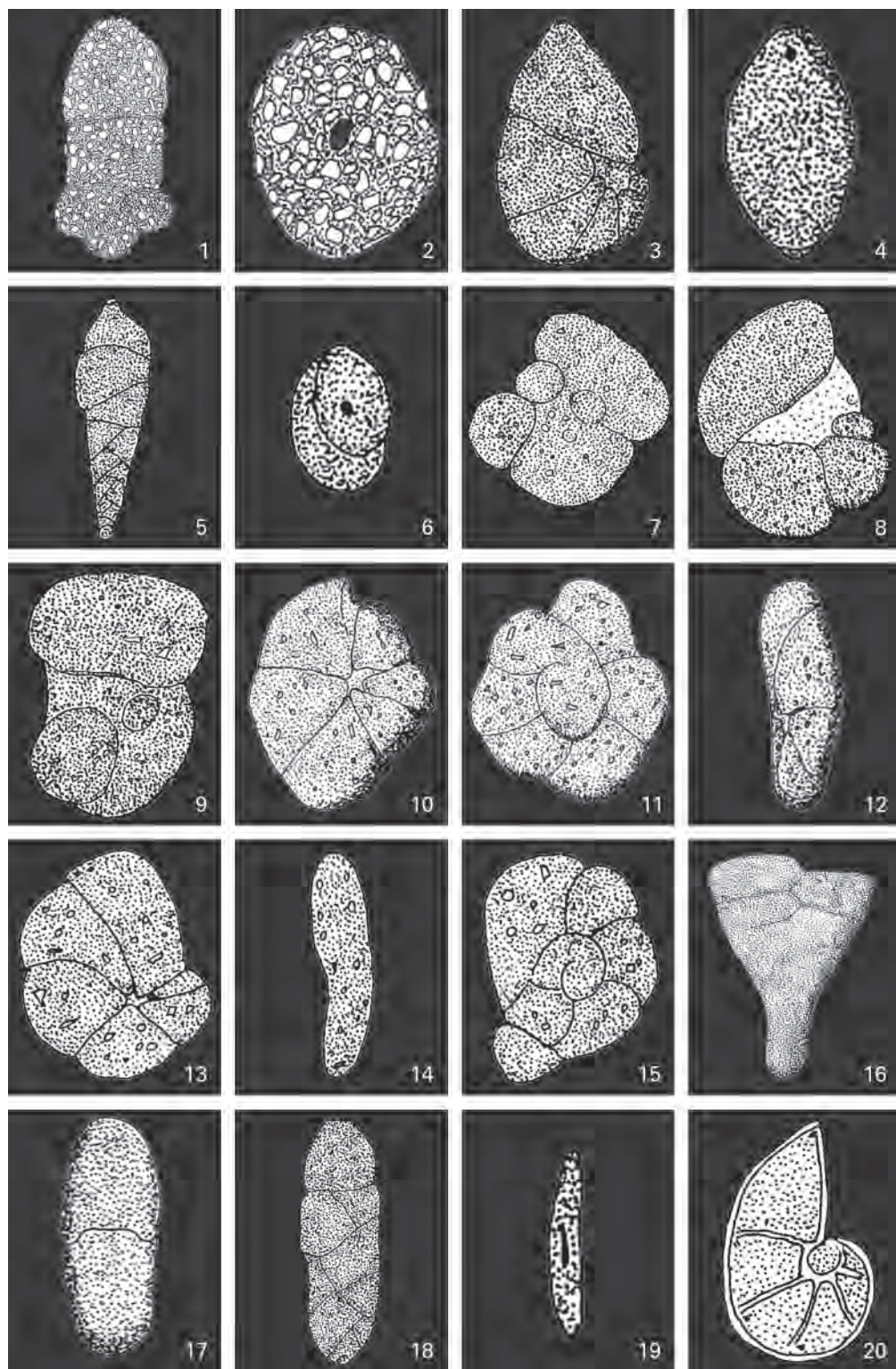
Fig. 23, nos 3–4; Fig. 25, nos 3–7.

DESCRIPTION

Test small, elongate, inflated, with chambers arranged in an initial involute, planispirally coiled portion composed of about four distinctly inflated chambers, and a later uncoiled rectilinear and uniserial portion, also composed of about four chambers, with all chambers increasing very slightly in size as added. Test periphery usually broadly rounded, and there is a distinct shallow umbilical depression developed on both sides of the test. Sutures depressed, initially rather indistinct, becoming distinct later, straight and mostly radiate in coiled part of test, but becoming strongly oblique in uncoiled part. Aperture small, a terminal subcircular opening located at the outer margin of the terminal face of the last-formed chamber. Test wall composed mostly of fine uniform quartz grains with occasional, irregularly scattered larger quartz grains, as well as sporadic black heavy mineral grains (ilmenite).

VARIATION

Little variation is apparent in the studied tests from the Bethelsdorp Formation. Some examples possess fewer larger-sized chambers in the uncoiled portion of the test, while other tests display more, smaller chambers. These differences may represent the microspheric and megalospheric generations respectively. All tests display the strongly oblique sutures of the uncoiled part of the test, and the peripherally-sited position of the aperture, which are the two principal diagnostic characteristics of this rather rare genus.



DERIVATIO NOMINIS

Named after the area where the borehole BT 1/74 was drilled, next to the Mission Salt Works, and near to the former site of the London Missionary Society's Bethelsdorp Mission.

NUMBER OF SPECIMENS

Six.

HOLOTYPE

Borehole BT 1/74, cuttings sample 339–342m. Fig. 23, nos 3–4.

STRATUS TYPICUS

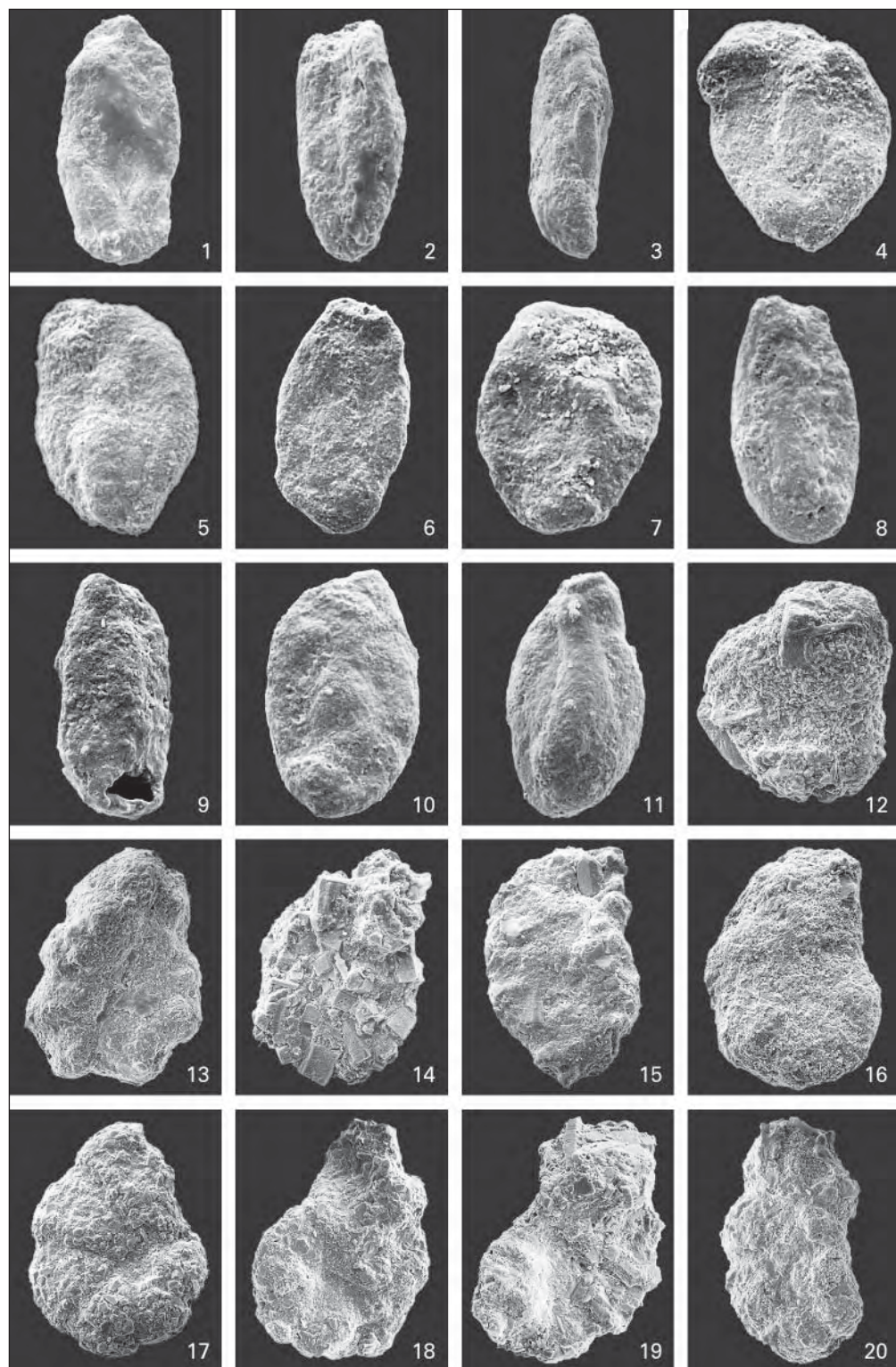
BT 1/74, cuttings sample 339–342m. This sample yielded the most numerous and the best-preserved tests of *Ammomarginulina missionensis* n. sp. Bethelsdorp Formation, Portlandian, onshore Uitenhage Trough, Algoa Basin.

PARATYPES

Four illustrated specimens figured as Fig. 25, nos 3–7.

FIGURE 23 (*facing page*)

1–2. *Ammobaculites subaequalis* Mjatluk. **1.** SAM-PQ-MF-2228. BT 1/74, 591–594m. Side view. $\times 48$. **2.** SAM-PQ-MF-2228. BT 1/74, 591–594m. Apertural view (same specimen as No. 1). $\times 183$. **3–4.** *Ammomarginulina missionensis* n. sp. McMillan. Holotype. **3.** SAM-PQ-MF-2229. BT 1/74, 339–342m. Side view. $\times 183$. **4.** SAM-PQ-MF-2229. BT 1/74, 339–342m. Apertural view (same specimen as No. 3). $\times 177$. **5–6.** *Plectinella aegyptiaca* (Said & Barakat). **5.** SAM-PQ-MF-2234. SW 1/08, 2948'. Side view. $\times 264$. **6.** SAM-PQ-MF-2234. SW 1/08, 2948'. Apertural view (same specimen as No. 5). $\times 160$. **7–9.** *Ammoglobigerina* cf. *A. globigeriniformis* (Parker & Jones). **7.** SAM-PQ-MF-2235. BT 1/74, 357–360m. Spiral view. $\times 256$. **8.** SAM-PQ-MF-2235. BT 1/74, 357–360m. Umbilical view (same specimen as No. 7). $\times 264$. **9.** SAM-PQ-MF-2235. BT 1/74, 357–360m. Edge view (same specimen as No. 7). $\times 264$. **10–12.** *Trochammina* cf. *T. inflata* (Montagu). **10.** SAM-PQ-MF-2236. BT 1/74, 411–414m. Umbilical view. $\times 256$. **11.** SAM-PQ-MF-2236. BT 1/74, 411–414m. Spiral view (same specimen as No. 10). $\times 240$. **12.** SAM-PQ-MF-2236. BT 1/74, 411–414m. Edge view (same specimen as No. 10). $\times 248$. **13–15.** *Trochammina* cf. *T. squamata* (Jones & Parker). **13.** SAM-PQ-MF-2237. BT 1/74, 591–594m. Umbilical view. $\times 320$. **14.** SAM-PQ-MF-2237. BT 1/74, 591–594m. Edge view (same specimen as No. 13). $\times 310$. **15.** SAM-PQ-MF-2237. BT 1/74, 591–594m. Spiral view (same specimen as 13). $\times 320$. **16–17.** *Dorothia* sp. **16.** SAM-PQ-MF-2238. BSP 11477. Side view. $\times 155$. **17.** SAM-PQ-MF-2238. BSP 11477. Apertural view (same specimen as No. 16). $\times 160$. **18–19.** *Bigenerina* sp. **18.** SAM-PQ-MF-2239. SW 1/08, 2948'. Side view. $\times 94$. **19.** SAM-PQ-MF-2239. SW 1/08, 2948'. Apertural view (same specimen as No. 18). $\times 71$. **20.** *Lenticulina* cf. *L. quenstedti* (Gümbel) forma A Wernli. SAM-PQ-MF-2240. SW 1/08, 2948'. Side view. $\times 160$.



REMARKS

If the generic description of *Ammomarginulina*, originally described from Holocene sediments, as given by Loeblich & Tappan (1964), is rigorously applied to the various species referred to the genus from Late Jurassic and Early Cretaceous rocks, it is evident that many should rather be referred to *Ammobaculites* or other genera. Wiesner (1931) originally gave the generic description as “Die sandige Schale anfangs spiraling aufgewunden, die späteren Kammern geradlinig andgeordnet; die Nähte schief, die Mündung am Rückenumfang.” Because of the consequent rather doubtful nature of almost all previously described Late Jurassic and Early Cretaceous species of *Ammomarginulina*, comparisons between *A. missionensis* n. sp. and similar species of the same age are not possible. *Ammomarginulina missionensis* differs from the type species, *A. ensis* Wiesner, described from Holocene sediments, in possessing fewer chambers in the uncoiled part of the test, and in displaying a smaller initial coil.

OCCURRENCE IN THE BETHELSDORP FORMATION

339 to 423m in BT 1/74; 1175 to 1445m in ST 1/71; 2140 to 2948' in SW 1/08; not in BSP.

FIGURE 24 (*facing page*)

1–3. *Miliammina buchenroderi* n.sp. McMillan. Paratype. **1.** SAM-PQ-MF-2191. BT 1/74, 339–342m. F16, side view. × 185. **2.** SAM-PQ-MF-2192. BT 1/74, 339–342m. F17, side view. × 200. **3.** SAM-PQ-MF-2193. BT 1/74, 339–342m. F15, side view. × 205. **4–7.** *Miliammina electra* n.sp. McMillan. Paratype. **4.** SAM-PQ-MF-2195. BT 1/74, 339–342m. F13, side view. × 280. **5.** SAM-PQ-MF-2196. BT 1/74, 339–342m. F14, side view. × 206. **6.** SAM-PQ-MF-2197. BT 1/74, 339–342m. F12, side view. × 226. **7.** SAM-PQ-MF-2198. BT 1/74, 258–261m. F1, side view. × 272. **8–11.** *Miliammina palustris* n.sp. McMillan. Paratype. **8.** SAM-PQ-MF-2201. BT 1/74, 339–342m. F11, side view. × 220. **9.** SAM-PQ-MF-2202. BT 1/74, 339–342m. F10, side view. × 226. **10.** SAM-PQ-MF-2203. BT 1/74, 339–342m. F9, side view. × 256. **11.** SAM-PQ-MF-2204. BT 1/74, 258–261m. F2, side view. × 220. **12–13.** *Haplophragmoides* sp. 1. **12.** SAM-PQ-MF-2207. BT 1/74, 285–288m. F4, side view. × 120. **13.** SAM-PQ-MF-2208. BT 1/74, 411–414m. F24, side view. × 128. **14–16.** *Haplophragmoides haeusleri* Lloyd. **14.** SAM-PQ-MF-2210. BT 1/74, 303–306m. F8, side view. × 109. **15.** SAM-PQ-MF-2211. BT 1/74, 303–306m. F6, side view. × 124. **16.** SAM-PQ-MF-2212. BT 1/74, 357–360m. F21, side view. × 128. **17–18.** *Haplophragmoides* sp. 3. **17.** SAM-PQ-MF-2352. BT 1/74, 411–414m. F27, side view. × 103. **18.** SAM-PQ-MF-2353. BT 1/74, 411–414m. F28, side view. × 85. **19.** *Ammobaculites* sp. 1. SAM-PQ-MF-2220. BT 1/74, 303–306m. F7, side view. × 180. **20.** *Ammobaculites* sp. 2. SAM-PQ-MF-2222. BT 1/74, 366–369m. F22, side view. × 132.

Family TEXTULARIOPSIDAE Loeblich & Tappan, 1982

Genus PLECTINELLA Marie, 1956

Plectinella aegyptiaca (Said & Barakat, 1958)

Fig. 23, nos 5–6.

Arenovirgulina aegyptiaca Said & Barakat, 1958: 243, pl. 3, fig. 38a–b.

REMARKS

A single specimen from the Bethelsdorp Formation appears referable to this mid-late Jurassic species. Said & Barakat (1958) described this species from the Callovian of the Gebel Maghara area, Sinai, Egypt. Test width of the South African specimen increases at a similar width as seen in the Egyptian specimens, and it shows the initial biserially arranged chambers very clearly. The height of the chambers in the Bethelsdorp test increase steadily, so that the early chambers are more broad than high, and the later ones are higher than broad. The aperture is a vertically aligned, narrow slit, extending up from the interior margin of the last-formed chamber up towards the terminal point of the test. These test morphology characteristics indicate that this Bethelsdorp test differs distinctly from those described under the name *Plectinella castlecliffensis* by McMillan (2003a) from the mid Valanginian beds of the basal Sundays River Formation. However, the environmental tolerances of the Bethelsdorp and Sundays River formation *Plectinella* are probably identical: hyposaline conditions within an estuarine sedimentary complex.

OCCURRENCE IN THE BETHELSDORP FORMATION

2948' in SW 1/08; not in BT 1/74, ST 1/71 or BSP.

Family TROCHAMMINIDAE Schwager, 1877

Subfamily TROCHAMMININAE Schwager, 1877

Genus AMMOGLOBIGERINA Eimer & Fickert, 1899

Ammoglobigerina cf. *A. globigeriniformis* (Parker & Jones, 1865)

Fig. 23, nos 7–9.

see *Lituola nautiloidea* Lamarck *globigeriniformis* Parker & Jones, 1865: 407, pl. 15, figs 46–47 (also possibly pl. 17, figs 96–98).

see *Trochammina globigeriniformis* (Parker & Jones); Cifelli, 1959: 290, pl. 1, figs 23–24; Lloyd, 1959: 317, pl. 54, fig. 31, text-fig. 5c; Bielecka, 1960a: 47, 120, pl. 1, figs 9a–b; Wernli, 1971: 315, pl. 8, figs 4, 9a–c; Barnard & Shipp, 1981, 9, pl. 1, figs 11–12; Coleman, 1981: 114, pl. 6.2.1, fig. 11.

see *Trochammina canningensis* Tappan; Welzel, 1968: 7, pl. 1, figs 13a–b.

see '*Trochammina*' sp. cf. *T. globigeriniformis* (Parker & Jones); Masiuk & Viña, 1987: 292, pl. 2, figs 4–8, 11.

REMARKS

The taxonomic status of *Globigerina*-like tests with an agglutinated test wall, formerly referred to *Trochammina globigeriniformis* (Parker & Jones), is unclear. This is especially so of the Jurassic records to the species, which was originally described from Holocene sediments. The earliest record of this species from the European Jurassic succession appears to be that of Haeusler (1890), which in the revision by Oesterle (1968) these specimens were referred partly to *Trochammina* cf. *canningensis* Tappan, and partly to *Trochammina rotundata* Seibold & Seibold.

The forms described by Tappan (1955) from the Jurassic of Alaska as *Trochammina canningensis* appear to be distinct from the "*globigeriniformis*"-like tests detailed by such authors as Cifelli (1959), Lloyd (1959), Bielecka (1960a), Welzel (1968), Wernli (1971), Barnard & Shipp (1981) and Coleman (1981). Tappan (1955) notes that *Trochammina canningensis* has "more chambers per whorl" than *Trochammina globigeriniformis* – four to seven in the final whorl – and the shape of the test is somewhat different. Additional taxonomic comments on this confusing Jurassic to Early Cretaceous group of agglutinated-walled foraminifera are presented by McMillan (2003a, p. 93).

So far as can be seen the tests from the Bethelsdorp Formation are unlike those detailed (both the low-spined and high-spined forms) from the Early Cretaceous rocks of the Sundays River Formation (McMillan, 2003a), in the height of spire and especially the chamber outline. However, test preservation of the few Bethelsdorp Formation examples is poor, owing to diagenetic distortion. McMillan (2003a) regarded these forms as being dysaerobic environmental indicators in the Sundays River Formation, and the same is taken to be the case here in the Bethelsdorp Formation.

Cifelli (1959) detailed tests from the English Bathonian, Lloyd (1959) and Barnard & Shipp (1981) from the Kimmeridgian of Dorset, and the species group ranges through much of the Lias and Dogger of England (Coleman, 1981); Welzel (1968) detailed tests from the Domerian (Lias) of Germany, Bielecka (1960a) from the Oxfordian-Callovian of southern Poland, and Wernli (1971) from the Aalenian to Oxfordian of southern France.

OCCURRENCE IN THE BETHELSDORP FORMATION

357–360m, 420–423m in BT 1/74; 1175 to 1180m in ST 1/71; not in SW 1/08 or BSP.

Genus TROCHAMMINA Parker & Jones, 1859

Trochammina cf. *T. inflata* (Montagu, 1808)

Fig. 23, nos 10–12.

see *Nautilus inflatus* Montagu, 1808: 81, pl. 18, fig. 3.

see *Trochammina inflata* (Montagu); Bartenstein & Brand, 1951: 280, pl. 4, fig. 98 (?not fig. 97); Lutze, 1960: 447, pl. 28, figs 1–3.

see *Trochammina* cf. *T. inflata* (Montagu); McMillan, 2003a: 94, figs 33A–D.

REMARKS

The various forms described as *Trochammina inflata* from Jurassic and Cretaceous sediments are morphologically similar to this species originally described from the Holocene, but they are probably not conspecific. The Bethelsdorp Formation specimens are distinctly but subtly different (especially in chamber shape) from those detailed from the Late Valanginian to Hauterivian sediments of the Sundays River Formation (McMillan, 2003a), and it seems best to consider this group a plexus, probably with polyphyletic origins, ranging through the later Mesozoic and Cainozoic to the present day. That this is true is probably best reflected in the wide range of depositional environments in which this “species” is encountered: with living *Trochammina inflata* sensu stricto being confined to salt marsh. From published literature the Bethelsdorp Formation specimens are closely similar to the test illustrated by Bartenstein & Brand (1951) on plate 4, fig. 98, but this illustration is a pen-and-ink drawing that may not be fully representative.

OCCURRENCE IN THE BETHELSDORP FORMATION

411–414m, and 420–423m in BT 1/74; 1175 to 1375m in ST 1/71; not in SW 1/08 or BSP.

Trochammina cf. *T. squamata* Jones & Parker, 1860

Fig. 23, nos 13–15.

Trochammina squamata sensu Gordon, 1967: 451, pl. 1, fig. 15 (*non* Parker & Jones).

REMARKS

As with *Trochammina inflata*, a considerable degree of variation exists between different authors’ interpretations of the Jurassic and Early Cretaceous forms referred to *Trochammina squamata*, also originally described from Holocene sediments. The single specimen from the Bethelsdorp Formation is most closely comparable to the test illustrated by Gordon (1967) from the Callovian of Brora, Scotland, but it is slightly crushed. This group of morphologically similar tests is considered to be a plexus, again with multiple origins, which cannot easily be taxonomically resolved.

OCCURRENCE IN THE BETHELSDORP FORMATION

591–594m in BT 1/74; not in ST 1/71, SW 1/08 or BSP.

Trochammina spp.

REMARKS

Occasional specimens referable to *Trochammina* were noted in all studied borehole sections from the Uitenhage Trough. Poor preservation, and, in the case of some tests, slight test compaction from diagenesis, have prevented specific identifications.

OCCURRENCE IN THE BETHELSDORP FORMATION

303 to 603m in BT 1/74; 1240 to 1285, 1380–1385m, 1410 to 1445m in ST 1/71; 2100' and 2948' in SW 1/08; not in BSP.

Family EGGERELLIDAE Cushman, 1937
Subfamily DOROTHIINAE Balakhmatova, 1972
Genus DOROTHIA Plummer, 1931

Dorothia sp.
Fig. 23, nos 16–17.

REMARKS

A single deformed test that can be referred to this genus was found in the Bethelsdorp Formation. This test is conical in outline, with the chambers increasing regularly in width as added. The test wall is composed of finely agglutinated quartz grains throughout, and is almost glassy in appearance. The chamber morphology and the test outline of this specimen are unlike those of *Dorothia australis*, described from the Late Valanginian and earliest Hauterivian portion of the Sundays River Formation by McMillan (2003a). It has not proven possible to establish whether there are canaliculi through the test wall.

OCCURRENCE IN THE BETHELSDORP FORMATION

BSP 11477; nowhere else.

Family TEXTULARIIDAE Ehrenberg, 1838

Subfamily TEXTULARIINAE Ehrenberg, 1838

Genus BIGENERINA d'Orbigny, 1826

Bigenerina sp.

Fig. 23, nos 18–19.

REMARKS

A small number of poorly preserved specimens may be referable to this genus. The specimens have been slightly compressed, and the form of the initial part of the test is not too clear. The chambers are arranged biserially for most of the test, with only one or two uniserial chambers on the final part of the test. The aperture is terminal and centrally sited. Because of the preservation, no attempt has been to compare them with other previously described species.

OCCURRENCE IN THE BETHELSDORP FORMATION

2948' in SW 1/08; nowhere else.

Family CORNUSPIRIDAE Schultze, 1854

Subfamily CORNUSPIRINAE Schultze, 1854

Genus CORNUSPIRA Schultze, 1854

Cornuspira orbicula (Terquem & Berthelin, 1875)

Fig. 25, nos 8–9.

Spirillina orbicula Terquem & Berthelin, 1875: 17, pl. 1, figs 12a–c.

Cornuspira orbicula (Terquem & Berthelin); Bartenstein & Brand, 1951: 279, pl. 4, fig. 89; Bartenstein, 1956: 514, fig. 64.

REMARKS

As in several other simple, planispirally coiled tubular forms described in the 19th century, some confusion has arisen over whether the wall structure of *Spirillina orbicula*, as originally described, is calcareous and perforate (implying a true *Spirillina*), or porcellaneous (implying a miliolid). The original description of the species indicates that the surface of the test is “lisse, translucide”. No mention is made of the test wall being perforated by pores. Most later authors have considered the species to be porcellaneous-walled, and their precedent is followed here.

The few specimens obtained from the Bethelsdorp Formation in the onshore portion of the Uitenhage Trough compare closely with the morphological description given by Terquem & Berthelin (1875). Some tests consist only of smooth-surfaced pyrite internal casts, with no trace of the original shell remaining, but the obvious absence

of any markings attributable to test perforations on the pyrite surface confirms a porcellaneous test wall also for these tests.

Terquem & Berthelin (1875) described this species from the middle Lias of France; Bartenstein & Brand (1937) obtained specimens from the lowest Lias of north-west Germany; Frentzen (1942) listed the species in the Bajocian of southern Germany; Bartenstein & Brand (1951) recorded it from the Valanginian of north-west Germany; Bartenstein (1956) noted it from the Hauterivian of England. Bielecka (1960a) noted *Spirillina orbicula*, which may or may not be the same species from the Oxfordian of the Piekary borehole, near Poznań, Poland. Said & Barakat (1958) detailed *Cornuspira* cf. *orbicula* from the Bathonian of Gebel Maghara, Sinai Peninsula, Egypt. Whether these conservative forms are all conspecific is difficult to determine.

OCCURRENCE IN THE BETHELSDORP FORMATION

420–423m in BT 1/74; 1400–1405m in ST 1/71; 2948' in SW 1/08; not in BSP.

Family HEMIGORDIOPSIDAE A. Nikitina, 1969

Subfamily HEMIGORDIOPSINAE A. Nikitina, 1969

Genus ORTHOVERTELLA Cushman & Waters, 1928

?*Orthovertella* sp.

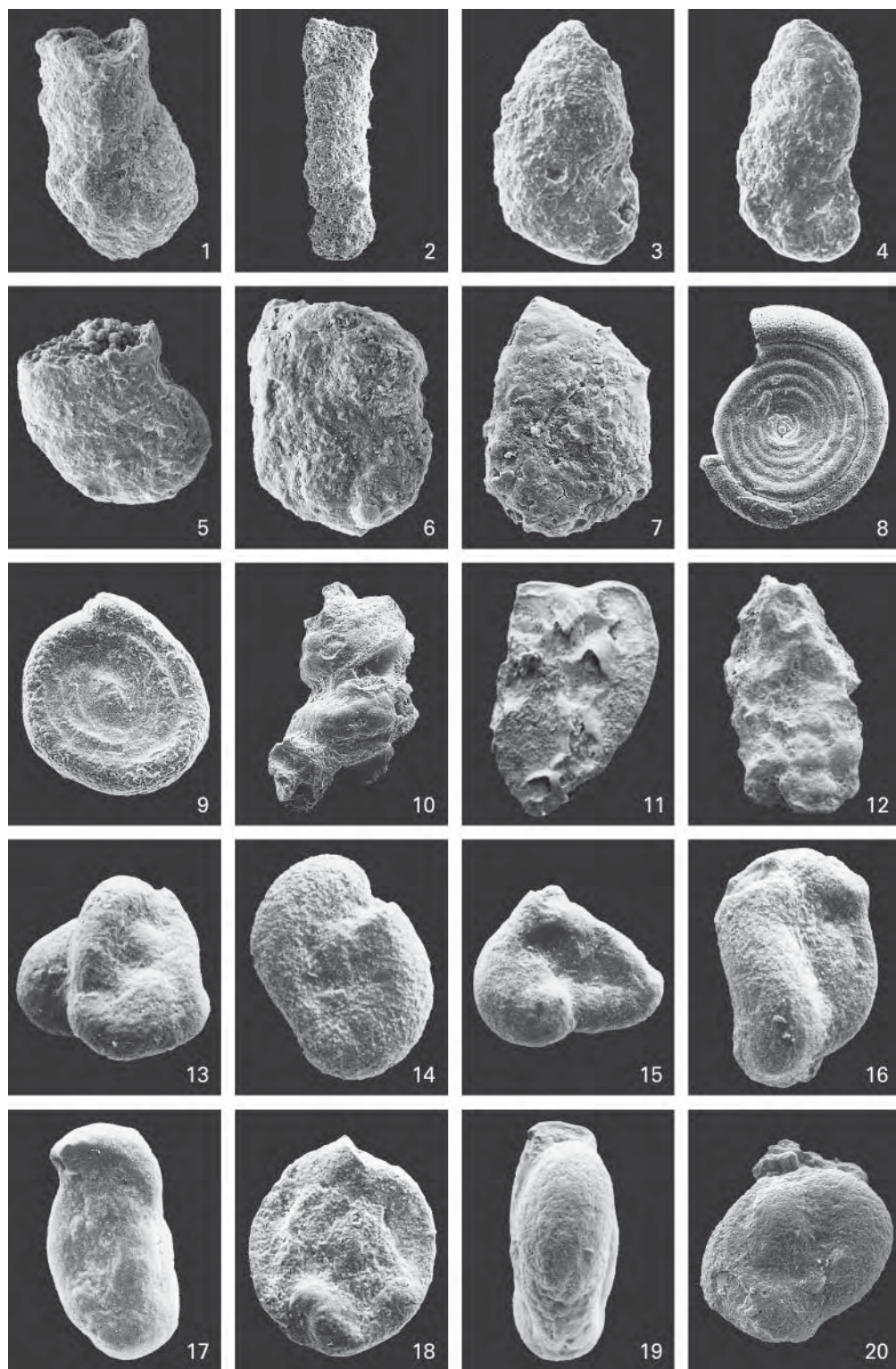
Fig. 25, no. 10.

REMARKS

A small number of porcellaneous-walled, irregularly-coiled forms, all composed of a single non-chambered tube, occur mostly in the topmost Bethelsdorp Formation, just below the highest occurrences of marine fossils in the borehole sections. All specimens are poorly preserved, but appear to be closely related to the genus *Orthovertella*; they differ from that genus in lacking a later uncoiled section of the test, which may, of course, have been lost through test damage.

OCCURRENCE IN THE BETHELSDORP FORMATION

258–261m in BT 1/74; 1090–1095m in ST 1/71; 2866' in SW 1/08; not in BSP.



Family NUBECULARIIDAE Jones, 1875

Subfamily NUBECULARIINAE Jones, 1875

Genus NUBECULARIA Defrance, 1825

Nubecularia lucifuga Defrance, 1825

Fig. 25, nos 11–12.

Nubecularia lucifuga Defrance, 1825: 210, pl. 44, figs. 3, 3a–d; Jones & Parker, 1860b: 455, pl. 20, figs 52–56; Arnold, 1967: 622, text-figs 1–12; McLachlan *et al.*, 1976b: 328.

REMARKS

In a detailed examination of natural and cultured living specimens of “*Nubecularia lucifuga*”, and comparison of them with fossil examples of the same species, Arnold (1967) drew attention to the confusion surrounding the taxonomy of this and other similar species. He concluded that “in the light of this (Arnold’s) study of variability in natural and culture populations, careful examination of original descriptions of the thirty-odd species of living and fossil *Nubecularia*, (and a not insignificant number of species assigned to other genera as well!) suggests quite strongly that almost half of them should more properly be assigned to *N. lucifuga*”. All *Nubecularia* specimens

FIGURE 25 (*facing page*)

1–2. *Ammobaculites* sp. 2. **1.** SAM-PQ-MF-2223. BT 1/74, 411–414m. F26, side view. $\times 113$. **2.** SAM-PQ-MF-2224. BT 1/74, 411–414m. F29, side view. $\times 106$. **3–7.** *Ammomarginulina missionensis* n.sp. Paratype. **3.** SAM-PQ-MF-2230. BT 1/74, 339–342m. F1311, side view. $\times 226$. **4.** SAM-PQ-MF-2231. BT 1/74, 339–342m. F1312, side view. $\times 188$. **5.** SAM-PQ-MF-2232. BT 1/74, 339–342m. F20, side view. $\times 180$. **6.** SAM-PQ-MF-2233. BT 1/74, 339–342m. F19, side view. $\times 226$. **7.** SAM-PQ-MF-2234. BT 1/74, 339–342m. F18, side view. $\times 212$. **8–9.** *Cornuspira orbicula* (Terquem & Berthelin). **8.** SAM-PQ-MF-2241. BT 1/74, 420–423m. F1314, side view. $\times 240$. **9.** SAM-PQ-MF-2242. ST 1/71, 1400m. Core 1, F1315, side view. $\times 216$. **10.** ?*Orthovertella* sp. SAM-PQ-MF-2243. BT 1/74, 258–261m. F1313, side view. $\times 207$. **11–12.** *Nubecularia lucifuga* Defrance. **11.** SAM-PQ-MF-2354. BSP 4901. Attached to shell fragment, F1371. $\times 49$. **12.** SAM-PQ-MF-2355. BSP 4901. Attached to shell fragment, F1370, $\times 69$. **13–17.** Wild growing *Quinqueloculina grisbrooki* n.sp. McMillan. Paratype. **13.** SAM-PQ-MF-2245. BT 1/74, 294–297m. F1275, side view. $\times 142$. **14.** SAM-PQ-MF-2246. BT 1/74, 447–450m. F1279, side view. $\times 206$. **15.** SAM-PQ-MF-2247. BT 1/74, 357–360m. F1278, side view. $\times 125$. **16.** SAM-PQ-MF-2248. BT 1/74, 447–450m. F1280, side view. $\times 256$. **17.** SAM-PQ-MF-2249. ST 1/71, 1150–1155m. F1281, side view. $\times 256$. **18.** Massiline *Quinqueloculina grisbrooki* n.sp. McMillan. Paratype. SAM-PQ-MF-2250. BT 1/74, 294–297m. F1274, side view. $\times 160$. **19.** Normal *Quinqueloculina grisbrooki* n.sp. McMillan. Paratype. SAM-PQ-MF-2251. BT 1/74, 447–450m. F1377, edge view. $\times 213$. **20.** Triloculine *Quinqueloculina grisbrooki* n.sp. McMillan. Paratype. SAM-PQ-MF-2252. BT 1/74, 258–261m. F3, side view. $\times 180$.

encountered in the Bethelsdorp Formation have been considered, in the light of Arnold's studies, to be referable to *Nubecularia lucifuga*.

This species was originally described from the Eocene of northern France (Defrance, 1825), and has since been widely recorded, particularly in Holocene sediments from high-energy, inter-tidal and shallow-marine wave-dominated environments. Other fossil records are from the Lias of Chellaston, England (Jones & Parker, 1860b; dating amended by Adams, 1962, p. 162); from the Late Valanginian of Mngazana, South Africa (McLachlan *et al.*, 1976b); from the Albian of the Netherlands (Ten Dam, 1950), under the name *Nubecularia triloculina*. Arnold (1967) obtained cultured individuals of *Nubecularia lucifuga* "indistinguishable from specimens of *N. triloculina*".

In consequence of Arnold's (1967) work, and also observations by the present author of sporadic occurrences of *Nubecularia lucifuga* along the present-day wave-dominated littoral of the south-east coast of South Africa, it can clearly be seen that appearances of this species in the Bethelsdorp Formation also reflect a turbulent, highly-oxygenated and wave-dominated environment. Such an environment occurs rarely through the Bethelsdorp Formation succession, since quiet water, mudflat to estuary, hyposaline to hypersaline environments were prevalent, which precluded colonisation by *Nubecularia* species. All specimens encountered in the Bethelsdorp Formation derive from molluscan shell-rich intervals towards the base of the unit in the borehole sections, and outcropping around Bethelsdorp Salt Pan. All specimens of this species were found attached to bivalve shell fragments.

OCCURRENCE IN THE BETHELSDORP FORMATION

BSP 4798, 4901, 4904, 11478; nowhere else.

Family HAUERINIDAE Schwager, 1876
 Subfamily HAUERININAE Schwager, 1876
 Genus QUINQUELOCULINA d'Orbigny, 1826

Quinqueloculina grisbrooki n. sp. McMillan
 Fig. 25, nos 13–20; Fig. 26, nos 1–6.

DESCRIPTION

Test small, smooth-walled, with no indication of surface ornamentation. Maximum width of test at about mid-height, and test outline generally from 1½ to twice as high as wide. Chambers arranged in a quinqueloculine manner throughout, inflated, increasing steadily in size as added, and broadly rounded at the test margin. The earlier chambers of the last-formed five scarcely protrude from the sides of the test, and in some examples are almost flush with the test surface. Sutures generally

distinct, depressed, usually curved. Aperture terminal in position, in form a broad arch surrounded by a thickened lip, and containing a small, short and faintly bifid tooth.

VARIATION

- This species occurs in large numbers throughout the Bethelsdorp Formation succession, and it is without doubt the commonest species. However, apart from its occurrence in the green claystones synchronous with the lower and middle Kirkwood Formation in boreholes Hb-D1 and Hb-P1 in the offshore portion of the Uitenhage Trough, *Quinqueloculina grisbrooki* n. sp. appears to be limited to the proximal Uitenhage Trough, and is not found in any of the coeval successions in the other basins of the southern offshore of South Africa. Three types of variation can be seen in this species:
- The usual quinqueloculine test is the most common form, and the description above is based on this group of specimens. However, within this group there is further variation. The outline of the test varies from ovate (commonest) to almost parallel-sided and rectangular (less common). The parallel-sided variation often occurs in tests in which the last two chambers are staggered, one placed mostly above the mid-point of the test, and the other mostly below (see Fig. 26, no. 4). In these tests with an almost rectangular outline, there are just less than two chambers to the whorl, and the final two chambers wrap around strongly at the base and the top of the test.
- A second variation is evident as forms that are initially quinqueloculine, as described in detail above, but which later become triloculine. These tests possess three final chambers that are strongly inflated and almost globular, and which virtually conceal the earlier quinqueloculine chambers (see Fig. 25, no. 20). Only a small number of this variant have been obtained.
- A third variant is all the wild-growing forms. Many different variations exist: massiline forms in which the last-formed chambers are only biloculine in arrangement (compare with Heron-Allen & Earland, 1910); doubled forms, in which two chambers have been added side by side instead of one; and forms which change coiling direction by 180°.

When first dealing with this complex miliolid assemblage, attempts were made to subdivide it taxonomically along the lines of the variations detailed above, but it was found that none of the divisions were consistent and discrete across the entire assemblage. In consequence, the entire assemblage, including all variations, has been considered one species. Unpublished studies by the author on abundant specimens of an extant simple, unornamented *Quinqueloculina* species from Milnerton Lagoon, just north of Cape Town, display a similar range and similar types of variations (see also Murray, 1973). These miliolids were obtained from shallow water indentations into low grassy banks on the western margin of Milnerton Lagoon: this hypersaline “lagoonal” or lower estuarine environment was

destroyed, and its benthic foraminifera assemblages have disappeared, subsequent to the area being redeveloped as an island of coastal apartments protected from the sea by a continuous wall of steel piles driven into the estuary floor.

Tests of the *Quinqueloculina* species from Milnerton Lagoon often possessed turbellarian egg cases attached to them (see Boltovskoy & Wright, 1976, p. 41–43 for a review of epibiosis on foraminifera). Foraminifera specimens thus affected frequently grow later severely distorted chambers in an attempt to cover the attached egg case. A detailed examination of numerous tests of *Quinqueloculina grisbrooki* n. sp. failed to reveal any with comparable severely deformed or perforated chambers.

DERIVATIO NOMINIS

Named after apothecarist C.H. Grisbrook of Graaff-Reinet, geology enthusiast, who visited the Amsterdamhoek outcrops in 1828 (Grisbrook, 1830).

NUMBER OF SPECIMENS

Thirteen.

HOLOTYPE

Cuttings sample 357–360m, borehole BT 1/74, illustrated as Fig. 26, nos 1 and 5 (2 views of same specimen).

STRATUS TYPICUS

Cuttings sample 357–360m, borehole BT 1/74, Bethelsdorp Formation, Portlandian, onshore Uitenhage Trough, Algoa Basin.

PARATYPES

Twelve specimens from various samples, BT 1/74, illustrated as Fig. 25, nos 13–20 and Fig. 26, nos 2–4 and 6.

REMARKS

Few species of *Quinqueloculina* have been described from later Jurassic sediments. Lloyd (1962) described *Quinqueloculina egmontensis* from the type Kimmeridgian in southern England, and this species has been noted by several later authors from similarly-aged rock successions (Groiss, 1967; Bielecka, 1975: referred to the genus *Palaeomiliolina*). *Quinqueloculina grisbrooki* n. sp. differs from *Q. egmontensis* in possessing a tooth in the aperture, and in lacking any ornamentation of the test wall. *Quinqueloculina egmontensis* displays a surface ornamentation of a few narrow vertically-aligned, longitudinal ribs (Lloyd, 1962).

Cushman & Glazewski (1949) noted the presence of two species of *Quinqueloculina* in the Portlandian succession of the Ukraine (in Poland prior to 1945): *Quinqueloculina grisbrooki* differs from both species, neither of which was speciated. *Quinqueloculina*

sp. A is characterised by the presence of a projecting apertural neck, and in possessing unusually narrow chambers, while *Q.* sp. B is distinguished by a low, rounded test: none of these features have been seen in the South African tests.

Bizon (1958) detailed two questionable species of *Quinqueloculina* from the Oxfordian of coastal northern France. Neither of these species displays an apertural tooth, *Quinqueloculina* sp. 1 has the aperture developed on a neck, and there is a carinate margin to the test, while sp. 2 is marked by an oval test outline and a rounded test periphery. Tests of both species are poorly preserved, and no illustration was given for either species. *Quinqueloculina grisbrooki* may be similar to, or the same as sp. 2, but without further details of this French Oxfordian species, little comparison can be made.

Several authors have described species of *Quinqueloculina* from the early Cretaceous succession. Of these species only *Quinqueloculina minima* (Tappan, 1943), described from the Duck Creek Formation (Albian) of Texas and Oklahoma displays a test morphology comparable to that of *Quinqueloculina grisbrooki*, but it lacks an apertural tooth and its less inflated chambers are not seen in the South African species. *Quinqueloculina infravalanginiana* was described by Bartenstein (1962) from the Berriasian of Switzerland, but its tubular chambers and the bluntly pointed basal and apertural ends to the test are not seen in *Quinqueloculina grisbrooki* n. sp.

OCCURRENCE IN THE BETHELSDORP FORMATION

258 to 621m in BT 1/74; 1090 to 1455m in ST 1/71; 2040 to 2948' in SW 1/08; not in BSP.

Subfamily SIGMOILINITINAE Łuczkowska, 1974 Genus SIGMOILINA Schlumberger, 1887

Sigmoilina sp.

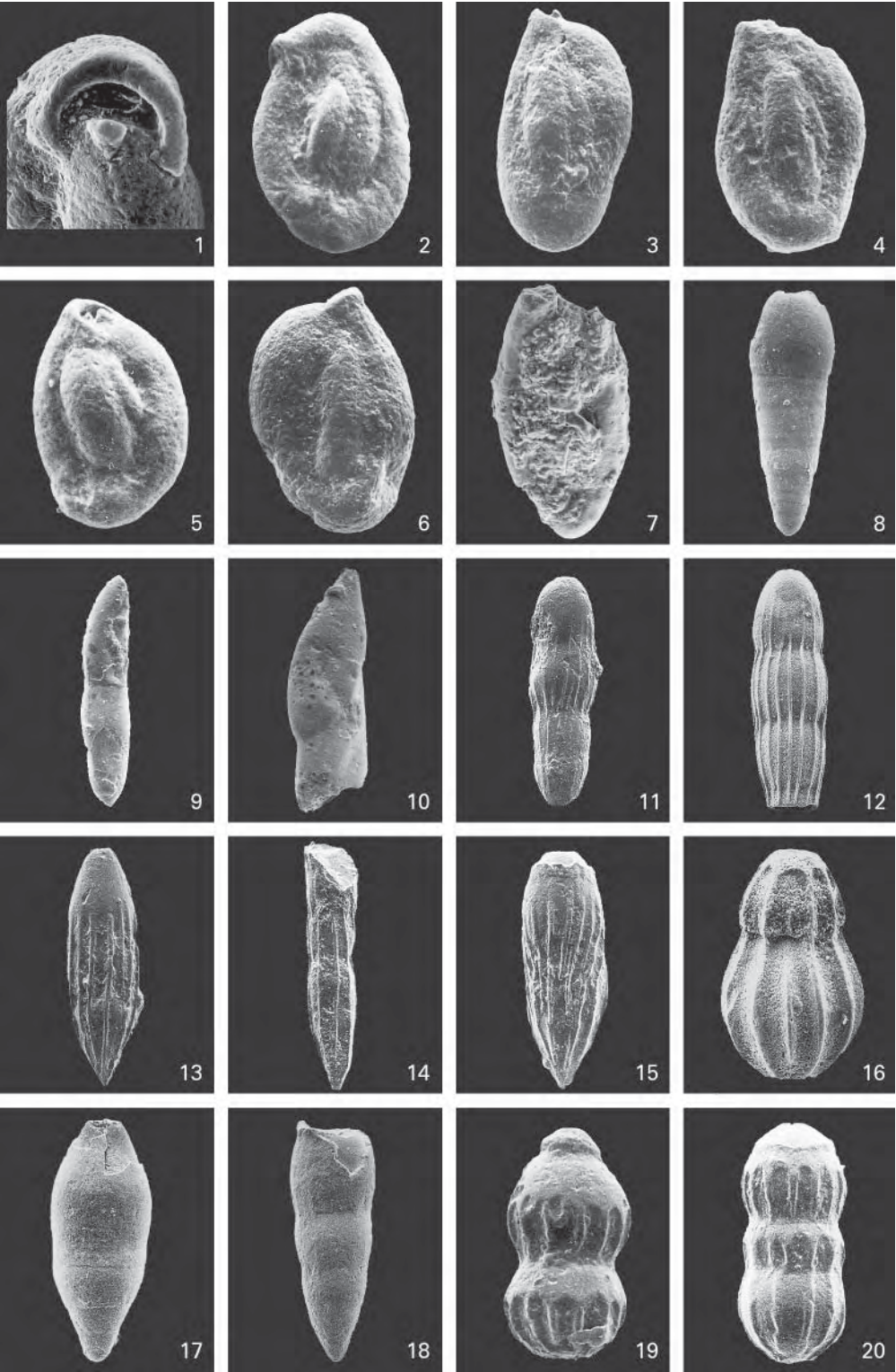
Fig. 26, no. 7.

REMARKS

A single, poorly preserved test, which shows the chambers arranged in the sinusoidal manner typical of the genus. The test wall is badly damaged, but is apparently smooth, and is not covered with siliciclastic grains as is the case in *Sigmoilopsis*. The poor material precludes a specific placing.

OCCURRENCE IN THE BETHELSDORP FORMATION

600–603m in BT 1/74; nowhere else.



Family ICHTHYOLARIIDAE Loeblich & Tappan, 1986
Genus LINGULONODOSARIA A. Silvestri, 1903

Lingulonodosaria nodosaria (Reuss, 1863)

Fig. 26, no. 8.

Lingulina nodosaria Reuss, 1863: 59, pl. 5, figs 12a–b.

Lingulina micida Loeblich & Tappan, 1950: 51, pl. 13, figs 29a–b, 30a–b.

REMARKS

A few small specimens from the Bethelsdorp Formation are referable to this species. Considerable differences in authors' interpretations of *Lingulonodosaria nodosaria* exist, but they are all clearly distinct from the formerly synonymous *Lingulina nodosaria* (Terquem) (see Wernli, 1971, p. 326). Reuss (1863) illustrated an elongate, unornamented form. Gordon (1962, 1965) illustrated specimens which are less elongate, show considerable variation in the height and degree of inflation of the chambers, and the degree of increase of chamber width as chambers are added. Gordon (1965) included *Lingulina micida* Loeblich & Tappan as a junior synonym.

FIGURE 26 (*facing page*)

1. Normal *Quinqueloculina grisbrooki* n.sp. McMillan. Holotype. SAM-PQ-MF-2244. BT 1/74, 357–360m. F1284/1285, close-up of aperture and tooth. × 512. **2.** Wild growing *Quinqueloculina grisbrooki* n.sp. McMillan. With embracing tubular final chamber. Paratype. SAM-PQ-MF-2253. BT 1/74, 294–297m. F1277, side view. × 177. **3–6.** Normal *Quinqueloculina grisbrooki* n.sp. McMillan. **3.** Paratype. SAM-PQ-MF-2254. BT 1/74, 411–414m. F1289, side view. × 165. **4.** Paratype. SAM-PQ-MF-2255. BT 1/74, 357–360m. F1287, side view. × 215. **5.** Holotype. SAM-PQ-MF-2244. BT 1/74, 357–360m. F1284, side view (same specimen as No. 2). × 256. **6.** Paratype. SAM-PQ-MF-2256. BT 1/74, 447–450m. F1290, opposite side view (same specimen as No. 20 on Fig. 25). × 272. **7.** *Sigmoilina* sp. SAM-PQ-MF-2257. BT 1/74, 600–603m. F1395, side view. × 226. **8.** *Lingulonodosaria nodosaria* (Reuss). SAM-PQ-MF-2258. BT 1/74, 375–378m. F23, side view. × 147. **9–10.** *Laevidentalina communis* (d'Orbigny). **9.** SAM-PQ-MF-2259. BT 1/74, 420–423m. F1360, side view. × 112. **10.** SAM-PQ-MF-2260. SW 1/08, 2866'. F1362, side view. × 40. **11–12.** *Pyramidulina* cf. *P. kuhni* (Franke). **11.** SAM-PQ-MF-2261. SW 1/08, 2948'. F1321, side view. × 141. **12.** SAM-PQ-MF-2262. BSP 11477, F1340, side view. × 132. **13.** *Pyramidulina minuta* (Cordey). SAM-PQ-MF-2263. SW 1/08, 2948'. F1318, side view. × 220. **14.** *Pyramidulina* narrower form of *P. minuta* (Cordey). SAM-PQ-MF-2264. BT 1/74, Core 2, 467.3m. F1319, side view. × 226. **15.** *Pyramidulina* cf. *P. minuta* (Cordey). SAM-PQ-MF-2265. SW 1/08, 2948'. F1320, side view. × 213. **16.** *Pyramidulina* sp. 1. SAM-PQ-MF-2266. BSP 11477, F1391, side view. × 146. **17–18.** *Nodosaria sowerbyi* Schwager. **17.** SAM-PQ-MF-2267. BT 1/74, 600–603m. F1328, side view. × 226. **18.** SAM-PQ-MF-2268. ST 1/71, 1200–1205m. F1329, side view. × 213. **19–20.** *Nodosaria* cf. *N. metensis* Terquem. **19.** SAM-PQ-MF-2269. SW 1/08, 2948'. F1317, side view. × 312. **20.** SAM-PQ-MF-2270. SW 1/08, 2948'. F1316, side view. × 272.

The South African tests compare well with Reuss's original illustration and description, but differ slightly in featuring a clearly narrower initial part of the test, which may be due to their being of the microspheric generation. Reuss (1863) described *Lingulonodosaria nodosaria* from the north German lowermost Gault ("Speeton Clay") of Early Cretaceous age. *Lingulina micida* was described from the Redwater Shale (Oxfordian) of South Dakota by Loeblich & Tappan (1950).

OCCURRENCE IN THE BETHELSDORP FORMATION

375–378m, 420–423m, 467.3m in BT 1/74; 2100' in SW 1/08; BSP 11475, 11476; not in ST 1/71.

Family NODOSARIIDAE Ehrenberg, 1838

Subfamily NODOSARIINAE Ehrenberg, 1838

Genus LAEVIDENTALINA Risso, 1826 *s.l.*

Laevidentalina communis (d'Orbigny, 1826) *s.l.*

Fig. 26, nos 9–10.

Nodosaria (Dentalina) communis d'Orbigny, 1826: 254 (illustration in d'Orbigny, 1840: pl. 1, fig. 4).

Dentalina communis (d'Orbigny); Bielecka & Pożaryski, 1954: 188, pl. 9, fig. 42; Bartenstein *et al.*, 1957: 34, pl. 7, figs 144a–b, 145; Neagu, 1965: 20, pl. 5, fig. 3; Bartenstein *et al.*, 1971: 147, abb. 3, fig. 59; Dailey, 1973: 63, pl. 8, fig. 15.

Dentalina communis (d'Orbigny) gr.; McLachlan *et al.*, 1976b: 330, fig. 16, no. 9.

Dentalina communis (d'Orbigny) *s.l.*; McMillan, 2003a: 156, fig. 49K–M.

REMARKS

D'Orbigny (1826) described this species from Holocene sediments of the Adriatic Sea. Later records range from Lias to the present day, and from many parts of the world, but it seems highly unlikely that they are all conspecific, and this long range is rather due to the conservative, unornamented and rather simple chamber arrangement within this group of *Laevidentalina*. The subtleties of degree of chamber inflation, height relative to width in the chamber shape, relative rectilinearity or arching in the overall shape of the test, and the presence or absence of radiate apertural slits, are structural features which all display considerable variation through time and place. The few tests of this group encountered in the Bethelsdorp Formation are morphologically unlike those from the Late Valanginian and Hauterivian rocks of the Sundays River Formation (McMillan, 2003a) and other contemporary South African rock successions (McLachlan *et al.*, 1976b).

OCCURRENCE IN THE BETHELSDORP FORMATION

420 to 423m in BT 1/74; 2866' in SW 1/08; not in ST 1/71 or BSP.

Laevidentalina spp.

REMARKS

The three studied borehole sections of the onshore Uitenhage Trough yielded a number of smooth-walled, unornamented tests that can be assigned to the genus *Laevidentalina*. Generally poor preservation and broken tests prevent their being identified to the specific level.

OCCURRENCE IN THE BETHELSDORP FORMATION

420–423m, 591–594m in BT 1/74; 1400m in ST 1/71; 2948' in SW 1/08; not in BSP.

Genus PYRAMIDULINA Fornasini, 1894

Pyramidulina cf. *P. kuhni* (Franke, 1936)

Fig. 26, nos 11–12.

see *Nodosaria kuhni* Franke, 1936: 46, pl. 4, fig. 13; Welzel, 1968: 14, pl. 1, fig. 29.

REMARKS

Three tests compare closely with *Pyramidulina kuhni* (Franke). The illustration and description of this species given by Franke (1936) features a *Pyramidulina* distinguished by a surface ornament of long low ribs aligned vertically or longitudinally over the test surface. Franke (*op. cit.*) noted that the ribs are higher and thicker over each transverse sutural depression. Thickening of the surface ribs over the sutures is only faintly apparent in the examples from the Bethelsdorp Formation. As in the illustration given by Welzel (1968) the South African tests display a distinctly less extensive coverage of surface ribs than that shown by Franke (1936), and, on the last-formed part of the test, these ribs are almost completely confined to the sutural depressions.

The distinctive initial spine characteristic of German tests of this species (Franke, 1936) is not clearly present in any tests from the Bethelsdorp Formation. However, in all other respects, especially the general test morphology, these South African tests are closely comparable to Franke's species. Franke (1936) described *Pyramidulina kuhni* from the Lias γ (Pliensbachian) beds near Bamberg, Bavaria, Germany.

OCCURRENCE IN THE BETHELSDORP FORMATION

2948' in SW 1/08; BSP 11477; not in BT 1/74 or ST 1/71.

Pyramidulina minuta (Cordey, 1962)

Fig. 26, nos 13–14.

Nodosaria (or *Dentalina*) *multicostata* Wisniowski, 1890: 196, pl. 8, fig. 44 (non *N. multicostata* d'Orbigny, 1840).

Nodosaria balteata Loeblich & Tappan, 1950: 49, pl. 13, figs 6–8.

Nodosaria minuta Cordey, 1962: 390, pl. 47, fig. 27.

REMARKS

Cordey proposed the name *Nodosaria minuta* as a new name for Wisniowski's species, which is a junior synonym of a species created by d'Orbigny. However, the validity of *Nodosaria balteata* over *Nodosaria minuta* is uncertain, and for the moment the name *Pyramidulina minuta* has been used.

Wisniowski described this species as possessing an ornamentation of “about twelve” vertically-aligned ribs, while Loeblich & Tappan (1950) noted *Nodosaria balteata* as having “about 14 low longitudinal ribs”. Gordon (1965), in describing a single test that he referred to *Nodosaria balteata*, described the ornamentation as follows: “Ten ribs commence at the extremity of the proloculum, and others are inserted between these later on, so that there are 17 at the aperture. There is no branching of the ribs”. In contrast, Cordey (1962) described his specimens of *Nodosaria minuta* as displaying an ornamentation of “numerous fine striae”.

Although all these forms are extremely similar in all other respects, the variation in the surface ornamentation has caused some difficulty in the interpretation. The characteristic style of the surface ornamentation has been taken to be those of Wisniowski (1890) and of Loeblich & Tappan (1950). Tests from the Bethelsdorp Formation compare closely to this, except that the Uitenhage Trough tests differ slightly in being ornamented with about 14 vertically aligned ribs, which become less distinct on the last-formed chamber. The area around the aperture is completely devoid of ornamentation in the South African tests.

Wisniowski (1890) described his species *Pyramidulina multicostata* from the Late Oxfordian beds from near Kraków, Poland. Loeblich & Tappan (1950) described *Pyramidulina balteata* from the Oxfordian Redwater Shale of South Dakota, USA. Cordey obtained his tests of *Pyramidulina minuta* from the Early Oxfordian Oxford Clay of the Isle of Skye, Scotland. Gordon's single test of *Pyramidulina balteata* was from the Early Oxfordian Nothe Grit of southern England.

OCCURRENCE IN THE BETHELSDORP FORMATION

420–423m, 467.3m, 591–594m in BT 1/74; 1250–1255m in ST 1/71; 2100' and 2948' in SW 1/08; BSP 11475, 11476, 11477.

Pyramidulina cf. *P. minuta* (Cordey, 1962)

Fig. 26, no. 15.

see *Nodosaria minuta* Cordey, 1962: 390, pl. 47, fig. 27.

REMARKS

Two specimens of a form closely comparable to the previous species were separated from it on differences in ornamentation. These two tests are similar in size and shape of test, but the surface ornamentation consists of many small vertically aligned ribs (about 18), which extend over the entire test. These ribs are in some places developed at a slight angle to the length of the test, so that in some areas the ribs are more widely spaced, and elsewhere more closely spaced.

OCCURRENCE IN THE BETHELSDORP FORMATION

2948' in SW 1/08; 11476 in BSP; not in ST 1/71 or BT 1/74.

Pyramidulina sp. 1

Fig. 26, no. 16.

REMARKS

A small number of distinctive specimens from the Bethelsdorp Salt Pan outcrops proved difficult to assign to a particular genus. They most closely resemble *Lagena*. Similar forms from the Early Cretaceous succession on the north-west Australian continental margin have been allocated to the genus *Pyramidulina* by Holbourn & Kaminski (1997). All five tests are composed of an initial large globular proloculus, followed by a second, much smaller hemispherical chamber. All tests feature a small opening or depression at the apical point of the test, possibly where an apical spine was formerly attached. The aperture is a terminal, circular opening. The surface of the test is ornamented with either nine (one example) or ten (four examples) strong, vertically aligned ribs, which are subangular to bladed in form.

Since the number of chambers and the size ratio of first to second chamber are the same in all five specimens, the possibility that they are juveniles of a uniserial, rectilinear genus, such as *Nodosaria* or *Pseudonodosaria*, seems unlikely. The additional second chamber places doubt on an allocation to *Lagena*, although interestingly, Loeblich & Tappan (1964, p. C518) previously described the genus as possessing a test which is "unilocular, rarely two or more chambers" in its arrangement.

Excluding the presence of the smaller second chamber, in all other respects these specimens appear very similar to *Lagena* cf. *L. sulcata* (Walker & Jacob), described by various authors from Early Cretaceous rocks, and discussed here on page 130.

OCCURRENCE IN THE BETHELSDORP FORMATION

Only in BSP 11476 and 11477.

Genus NODOSARIA Lamarck, 1812

Nodosaria sowerbyi Schwager, 1867

Fig. 26, nos 17–18.

Nodosaria sowerbyi Schwager, 1867: 656, pl. 34, fig. 8; Gordon, 1961: 529; Gordon, 1965: 849, text-fig. 7, nos 8–11.

REMARKS

Tests referred to this species in the three onshore Uitenhage Trough borehole successions are very similar to the tests described and illustrated by Schwager (1867). Several of the South African tests display chambers that are not as high as the chambers of Schwager's specimen, and they appear to be intermediate in a generic sense between *Pyramidulina* and *Pseudonodosaria*. This is especially noticeable because of the relatively rapid increase in the width of the chambers, and the slight overlap of the chambers, as added. The tests tending more near to *Pseudonodosaria* show some similarities also to *Nodosaria fusiformis* (Schwager), particularly as illustrated by Gordon (1965).

Schwager (1867) described *Nodosaria sowerbyi* on the basis of specimens from the *sowerbyi*-zone (Bajocian) of Aargau, Switzerland. Gordon (1961) obtained one example from the Ampthill Clay (Oxfordian) in Cambridgeshire, and further tests (Gordon, 1965) from the Nothe Grit, Nothe Clay and Ringstead Waxy Clay, Dorset (Early and Late Oxfordian), all of southern England.

OCCURRENCE IN THE BETHELSDORP FORMATION

2100', 3023' in SW 1/08; 1190–1195m in ST 1/71; 357–360m, 420–423m, 467.30m in BT 1/74; not in BSP.

Nodosaria cf. *N. metensis* Terquem, 1863

Fig. 26, nos 19–20.

see *Nodosaria metensis* Terquem, 1863: 167, pl. 7, fig. 5a–b; Morris & Coleman, 1989: 216, pl. 6.3.5, fig. 5.

Nodosaria cf. *N. metensis* Terquem; Gordon, 1965: 848, fig. 7, no. 14.

REMARKS

Two foraminifera tests from the Bethelsdorp Formation are closely comparable to the *Nodosaria* cf. *N. metensis* of Gordon (1965). Gordon compared his material with the two species *Nodosaria metensis* Terquem and *Dentalina cognata* Terquem & Berthelin. The surface ornamentation evident on Gordon's specimens is extremely distinctive. It consists of a number of depressions (10 to 15 in Gordon's material) with broad, flat intervening ribs extending up from the base of each globular chamber, and terminating about midway up the chamber. The smooth-walled upper half of the chamber is thus flush with the tops of the ribs developed on the lower half of each chamber.

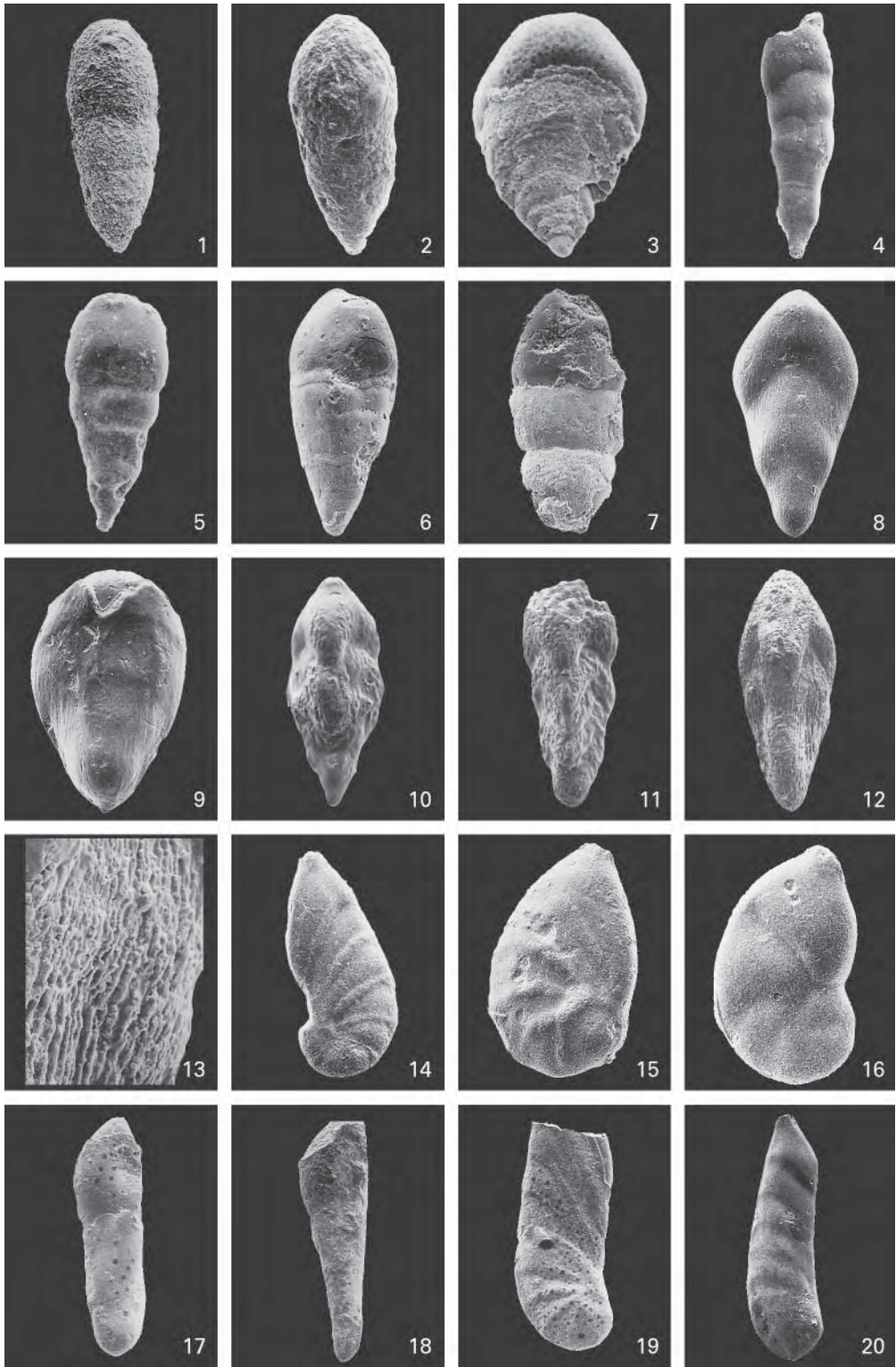
These elegant and distinctive tests are unlike *Pyramidulina metensis* (Terquem, 1863), as tests of that species display ribbed ornamentation over each entire chamber, but otherwise, especially in the form of the chambers, the two are similar. There is also a difference between these specimens and those of *Dentalina cognata*, both of which exhibit the same style of ornamentation, but *D. cognata* tests display sub-globular chambers and distinctly oblique sutures, and this species is definitely not referable to the genus *Nodosaria* or to *Pyramidulina*. Gordon (1965) considered that of the two specimens of *Dentalina cognata* originally illustrated by Terquem & Berthelin (1875, pl. 2, fig. 21a–b), that numbered 21a appeared closest to his southern English tests, as its sutures are closer to horizontal and transverse than those of the test numbered 21b.

It is felt that Gordon's material constitutes a new species, but as it has not proven possible to examine his specimens, the present two specimens from the onshore Uitenhage Trough have been referred to as *Nodosaria confer metensis*. All four of Gordon's specimens are damaged, and the two additional tests from the onshore Uitenhage Trough are also both damaged. In order to effectively describe and illustrate this species further, better-preserved tests are required. Of the two tests from the Bethelsdorp Formation, one consists of a proloculus followed by two chambers, while the second test consists of the two last-formed chambers, with one displaying the aperture. The proloculus of the first test is fully covered with ribs, but the characteristic ornamentation, as described above, is developed only on the second and later chambers. Here, the ribs extend over the lower $\frac{1}{2}$ to $\frac{2}{3}$ of each chamber. On the first specimen there are 12 ribs on each chamber; on the second, there are 13.

Gordon (1965) obtained his tests from the Nothe Clay, of earliest Late Oxfordian age, in Dorset, England. It is considered that this species is one of the strongest for emphasising a late Jurassic age for the Bethelsdorp Formation.

OCCURRENCE IN THE BETHELSDORP FORMATION

2948' in SW 1/08 only.



Subfamily LINGULININAE Loeblich & Tappan, 1961

Genus LINGULINA d'Orbigny, 1826

Lingulina dentaliniformis Terquem, 1870

Fig. 27, nos 1–2.

Lingulina dentaliniformis Terquem, 1870: 339, pl. 25, figs 1–3; Bartenstein & Brand, 1937: 152, pl. 10, fig. 20; Said & Barakat, 1958: 259, pl. 5, fig. 30; Wernli, 1971: 327, pl. 6, figs 12–16.

REMARKS

As noted by previous authors, *Frondicularia detaliniformis* Terquem and *Lingulina dentaliniformis* Terquem are either synonymous or very closely related species. The illustrations of the latter species given by Terquem (1870) show the aperture to be a very elongate, very narrow, terminally-sited slit. The tests from the Bethelsdorp Formation differ slightly in featuring a less elongate, rather broader apertural slit, similar to that of the tests figured by Wernli (1971). The sutures of the South African tests vary from horizontal to weakly arched. Those with horizontal sutures appear to be referable to *Lingulina dentaliniformis* forma A Wernli, but there are insufficient specimens from the Bethelsdorp Formation to justify separating them into two taxonomic units. Wernli (1971) noted that some examples show a rapid increase

FIGURE 27 (*facing page*)

1–2. *Lingulina dentaliniformis* Terquem. **1.** SAM-PQ-MF-2271. ST 1/71, 1220–1225m. F1364, side view. $\times 183$. **2.** SAM-PQ-MF-2272. BT 1/74, 420–423m. F1365, side view. $\times 194$. **3.** *Lingulina lamellata* Tappan. SAM-PQ-MF-2273. BT 1/74, 339–342m. F1381, side view. $\times 264$. **4–5.** *Lingulina lanceolata* (Haeusler). **4.** SAM-PQ-MF-2274. BT 1/74, 420–423m. F1366, side view. $\times 136$. **5.** SAM-PQ-MF-2275. BT 1/74, Core 2, 467.30m. F1367, side view. $\times 160$. **6–7.** *Lingulina* sp. **6.** SAM-PQ-MF-2276. BT 1/74, 294–297m. F5, side view. $\times 170$. **7.** SAM-PQ-MF-2277. BT 1/74, 411–414m. F25, side view. $\times 213$. **8.** *Frondicularia franconica* Gumbel. SAM-PQ-MF-2278. BSP 11478, F1344, side view. $\times 90$. **9.** *Frondicularia* sp. SAM-PQ-MF-2279. BSP 11478, F1374, side view. $\times 146$. **10–11.** *Tristix oolithica* (Terquem). **10.** SAM-PQ-MF-2280. BT 1/74, Core 2, 467.3m. F1385, side view. $\times 240$. **11.** SAM-PQ-MF-2281. BT 1/74, Core 2, 467.3m. F1386, side view. $\times 155$. **12–13.** *Tristix* sp. **12.** SAM-PQ-MF-2282. BSP 4798, F1387, side view. $\times 67$. **13.** SAM-PQ-MF-2282. Close-up of surface ornamentation BSP 4798, F1388 (same specimen as F1387). $\times 280$. **14.** *Astacolus* cf. *A. major* (Bornemann) forma A Lutze. SAM-PQ-MF-2284. BT 1/74, 591–594m. F1322, side view. $\times 116$. **15.** *Astacolus pellucida* Said & Barakat. SAM-PQ-MF-2285. SW 1/08, 2948'. F1325, side view. $\times 264$. **16.** *Astacolus* sp. SAM-PQ-MF-2286. BT 1/74, 609–612m. F1323, side view. $\times 220$. **17–18.** *Marginulina declivis* (Schwager). **17.** SAM-PQ-MF-2287. SW 1/08, 2948'. F1361, side view. $\times 150$. **18.** SAM-PQ-MF-2288. ST 1/71, Core 1, 1400m. F1363, side view. $\times 124$. **19–20.** *Vaginulinopsis* sp. **19.** SAM-PQ-MF-2289. BT 1/74, 591–594m. F1353, side view. $\times 91$. **20.** SAM-PQ-MF-2290. BSP 11477, F1375, side view. $\times 113$.

in width of chambers, whereas others increase in width very slowly, resulting in an almost parallel-sided test. The former are of the microspheric, and the latter of the megalospheric generation.

Lingulina dentaliniformis was described by Terquem (1870) from the *parkinsoni* Zone (highest Bajocian) of the Moselle area, France. Bartenstein & Brand (1937) described their material from the Dogger β (Late Aalenian) of north-west Germany, and Said & Barakat (1958) reported the species to occur in the Kimmeridgian succession of Gebel Maghara, northern Sinai, Egypt. Wernli (1971) recorded the range of this species as Late Aalenian to Early Oxfordian in the Jura Méridional of France.

OCCURRENCE IN THE BETHELSDORP FORMATION

294–297m, 375–378m, 420–423m, 467.0m, 467.30m in BT 1/74; 1220 to 1235m in ST 1/71; 2100' in SW 1/08.

Lingulina lamellata Tappan, 1940

Fig. 27, no. 3.

Lingulina lamellata Tappan, 1940: 106, pl. 16, fig. 19.

Fronicularia lamellata (Tappan); Bartenstein & Brand, 1951: 303, pl. 8, fig. 200 (and possibly fig. 201).

REMARKS

A single specimen of *Lingulina* agrees very well with the description given by Tappan (1940). The sutures grade from being arched in the early part of the test to chevron-shaped in the later part. Tappan (*op. cit.*, p.106) noted that the early chambers were “narrow, flaring suddenly and then enlarging gradually for the remainder of the length”. In contrast, the test from the Portlandian Bethelsdorp Formation features chambers that increase steadily in width, from earliest to latest. Bartenstein & Brand (1951) illustrated two tests, but that detailed as fig. 201 on plate 8 may be outside the limits of *Lingulina lamellata*, as originally described by Tappan.

Tappan (1940) described *Lingulina lamellata* from the Late Albian Grayson Formation of Texas (Frizzell, 1954 notes the Grayson to be Early Cenomanian). Bartenstein & Brand (1951) noted the range of this species in north-west Germany as Middle Valanginian to Early Hauterivian.

OCCURRENCE IN THE BETHELSDORP FORMATION

339–342m in BT 1/74 only.

Lingulina lanceolata (Haeusler, 1881)

Fig. 27, nos 4–5.

Frondicularia lanceolata Haeusler, 1881: 18, pl. 2, fig. 3.*Lingulina lanceolata* (Haeusler); Bartenstein & Brand, 1937: 151, pl. 2B, fig. 17; Tappan, 1955: 75, pl. 27, figs 5–6; Welzel, 1968: 35, pl. 2, fig. 17.

REMARKS

Some degree of variation in the interpretation of this species by later authors has been due to the slightly ambiguous original illustration and description given by Haeusler (1881). The few specimens from the Bethelsdorp Formation agree particularly well with the description and illustration of this species by Welzel (1968).

Haeusler (1881) described *Lingulina lanceolata* from the Schambelen outcrop (Oxfordian) in Canton Aargau, Switzerland. The specimen illustrated by Bartenstein & Brand (1937) derives from the Lias α^3 (Arietenstufe, Sinemurian) of north-west Germany. Tappan (1955) obtained specimens from the Kingak Shale (Late Pliensbachian) of South Barrow Test Well 3 in northern Alaska. Welzel's (1968) material was from the Domerian of southern Germany.

OCCURRENCE IN THE BETHELSDORP FORMATION

420–423m and 467.30m in BT 1/74; 2100' in SW 1/08; not in ST 1/71 or BSP.

Lingulina spp.

Fig. 27, nos 6–7.

REMARKS

Four small, damaged specimens of *Lingulina* were identified from the samples collected at Bethelsdorp Salt Pan and from the SW 1/08 borehole section. The four tests from the salt-pan outcrops do not warrant additional discussion, because of their damaged state. The two tests from SW 1/08 appear to be referable to the same species, and are similar to tests of *Lingulina lanceolata* (Haeusler), as reported above. One of these specimens also shows some similarities to *Frondicularia subtilis* Wisniewski. The other is somewhat similar to the *Frondicularia* sp. of the present study, but it differs in possessing a blade-like peripheral keel, a more flaring test, and occasional short vertical striations as surface ornamentation.

OCCURRENCE IN THE BETHELSDORP FORMATION

4904, 11476 at BSP; 2948' in SW 1/08; 1400m in ST 1/71; 411–414m and 438–441m in BT 1/74.

Subfamily FRONDICULARIINAE Reuss, 1860

Genus FRONDICULARIA Defrance, 1826

REMARKS

Authors studying Jurassic or Early Cretaceous foraminifera assemblages have often commented on the sometimes close morphological similarity of tests of the two genera *Lingulina* and *Fron dicularia*. Some species of *Lingulina* resemble species of *Fron dicularia*, but there are many other species of these two genera that do not possess counterparts in the other genus. In the case of the relationship between these two particular genera, there are two major morphological features of the test that have been utilised in attempts to effectively separate the two genera. Barnard (1963) and Wernli (1971), for example, have emphasised the angle and height of the chambers, with *Lingulina* species possessing convex, arched sutures and high chambers, whereas *Fron dicularia* species exhibit chevron-shaped sutures and low chambers which are strongly backward curving. In contrast, Loeblich & Tappan (1964), for example, have laid greater emphasis on the nature of the aperture: ovate to slit-like in the case of *Lingulina*, and circular in the case of *Fron dicularia*.

However, it would appear that in South African material available to the author through the years, both the form of the aperture and of the chambers and sutures show sufficient variation for a small degree of overlap to exist in the test morphology of the two genera. There is a gradation from low, chevron-shaped chambers to high, low-arched ones, and from slit-like to circular apertures, and these two variations are only partly associated with each other, and hence do not effectively constrain the limits of *Lingulina* and of *Fron dicularia*.

In the case of the foraminifera assemblages from the Late Valanginian to Hauterivian rocks of the Sundays River Formation documented by McMillan (2003a) there is a wide variety of *Lingulina* species. Forms identified as referable to *Lingulina bettenstaedti* (Zedler) (McMillan, 2003a, fig. 61G–H), with high-arched, poorly chevron-shaped chambers also display clear slit-like apertures. In contrast, forms identified as a new species *Lingulina trilobita* (McMillan, 2003a, fig. 61B–F), characterised by high, low-arched chambers, is also distinguished by an elongate, extremely thin slit-like aperture.

In the present study dealing with the foraminifera of the Bethelsdorp Formation, previous authors' precedents have been utilised where possible. In the case of species which could not be allocated to any previously described species, the nature of the aperture has been emphasised in allocating specimens either to *Lingulina* or *Fron dicularia*. Although five *Lingulina* species or species groups, and two of *Fron dicularia* have been recognised in the Bethelsdorp Formation, neither genus is common anywhere in the Bethelsdorp Formation and never to the frequency of these two genera encountered in the Sundays River Formation.

Frondicularia franconica Gümbel, 1862

Fig. 27, no. 8.

Frondicularia franconica Gümbel, 1862: 219, pl. 3, fig. 13a–c; Bartenstein & Brand, 1937: 153, pl. 15A, figs 17a–b; pl. 15C, figs 8a–b; Brand & Fahrion, 1962: 156, pl. 21, fig. 25; Cordey, 1962: 387, pl. 47, figs 20–21, text-figs 31–36.

Lingulina franconica (Gümbel); Seibold & Seibold, 1955: 119, pl. 13, fig. 8, text-fig. 3e.

Frondicularia franconica franconica Gümbel; Lutze, 1960: 470, pl. 32, figs 4, 6, 14.

REMARKS

Most authors have considered the species *Frondicularia franconica* Gümbel to be a true *Frondicularia*, as Gümbel's (1862) original illustration shows a circular, terminal aperture. However, a few authors, particularly Seibold & Seibold (1955) who re-examined and revised Gümbel's species, have regarded it as a species of *Lingulina*. Seibold & Seibold (1955) added that on the studied specimen the drawn-out apertural neck is mostly broken off. For the present study this species has been considered to be a *Frondicularia* species.

Many authors have noted the variation that this species exhibits. In particular, Lutze (1960), Cordey (1962) and Barnard (1963) have shown that the degree of lobation of the chambers along the test periphery varies considerably, as does the height of the arched sutures, and also the rate of increase of test width. Lutze (1960) established a number of subspecies on the basis of these variations, but Cordey (1962) regarded all the variations to grade into each other, and that they were not justified. In the examples from the Bethelsdorp Formation, all of which derive from the Bethelsdorp Salt Pan outcrops, a similar range of variations occurs to those detailed by Lutze. Only tests under the name *Frondicularia franconica impressa* Lutze were not encountered in the present study. In addition, two of the Bethelsdorp Formation tests display fine, vertically-aligned striations, and another example has developed a + shaped test, seen in cross-section. Because of variable preservation of these tests, not all of the Bethelsdorp Formation examples possess a clean aperture. Those that do, however, show the opening to be circular, usually marked by radiate slits, and only rarely raised on a very low apertural neck, similar to the low neck illustrated by Cordey (1962, text-figs 31–36).

Gümbel (1862) described *Frondicularia franconica* from the Oxfordian Schwamm-Mergeln of Streitberg, southern Germany. Bartenstein & Brand (1937) noted it from the Callovian to Early Oxfordian of north-west Germany, and Winter (1970) recorded it in the Early Kimmeridgian rocks of the Fränkischen Jura, southern Germany. Brand & Fahrion (1962) gave its range as Bathonian to Oxfordian in Germany, and Barnard (1963) as Callovian to Kimmeridgian in England.

OCCURRENCE IN THE BETHELSDORP FORMATION

4798, 4901, 4904, 11478 and 11479 in BSP only.

Frondicularia sp.

Fig. 27, no. 9.

REMARKS

A single specimen of a *Frondicularia* with a peripheral keel was found in the outcrop samples collected at Bethelsdorp Salt Pan. This test is elongate, with maximum width below mid-height. The early part of the test is compressed, and elongate-ovate in cross-section, while the later part is less compressed, and more ovate in cross-section. The test periphery is marked by a thickened, rounded keel that extends the full height of the test. Sutures are indistinct, flush with the test surface, and in form a moderately low, regularly curved arch. Foramen is terminal, a simple circular opening; the last-formed chamber is missing, and consequently the exact form of the aperture is unknown, for it may differ from that of the foramen. Surface of the test is smooth.

Only a small number of fossil species of *Lingulina*, and very few of *Frondicularia* are distinguished by a peripheral keel. Several such species have been described from the north-west European Lias succession: *Lingulina terquemi* Macfadyen (1941) appears similar in many respects, but can be distinguished on the basis of the lozenge-shaped cross-section to the test, whereas the South African test displays an ovate cross-section. *Frondicularia dubia* Terquem & Berthelin (1875) also shows similarities, but the chamber morphology in the later part of the test is distinctly different. The closest similarity would appear to be with *Frondicularia impressa* Terquem (1864), although in Terquem's species the chambers increase in width throughout the test, unlike in the specimen from Bethelsdorp Salt Pan.

Additional similarity exists between this single specimen from the Bethelsdorp Formation and rare tests described as *Lingulina loryi* (Berthelin) occurring in the Brenton Formation and in the equivalent of the Sundays River Formation (Late Valanginian to Hauterivian) in borehole PB-A1 (McLachlan *et al.*, 1976a). However, the test from the Bethelsdorp Salt Pan differs in possessing a much narrower test width. Additional comments on *Lingulina loryi* and its occurrence in South Africa are given under the discussion on *Lingulina* sp. A by McMillan (2003a, p. 210, fig. 62K).

OCCURRENCE IN THE BETHELSDORP FORMATION

Only 11475 BSP.

Genus TRISTIX Macfadyen, 1941

Tristix acutangula (Reuss, 1863)

Rhabdogonium acutangulum Reuss, 1863: 55, pl. 4, figs 14a–b.

Tristix acutangulus or *T. acutangula* (Reuss); Bartenstein & Brand, 1951: 314, pl. 10, figs 257–261; Lutze, 1960: 476, pl. 29, figs 1a–b; Bielecka, 1975: 354, pl. 10, figs 17–19; McMillan, 2003a: 224, figs 66H–K, 67A.

REMARKS

This species appears to be very similar to *Tristix suprajurassica*, described by Paalzow (1932) from the Oxfordian Transversarius-schichten of south-west Germany. Bielecka (1975) included some references to *Tristix suprajurassica* under *Tristix acutangula*, whereas Lutze (1960) has regarded the two species as fully synonymous. Magniez-Jannin (1975) analysed variations in test morphology of *Tristix acutangula* tests from the French Albian succession. She included tests with rounded peripheral angles and lacking a peripheral keel within the variation exhibited by this species.

Tests from the Portlandian Bethelsdorp Formation are either faintly carinate, or otherwise non-carinate and sub-angular at the test periphery. Following the species interpretation of Magniez-Jannin (1975), all of these tests are referred to *Tristix acutangula*. They are morphologically very similar to those previously described from the Late Valanginian to Hauterivian Sundays River Formation of the Algoa Basin, and in synchronous units in the Pletmos and Mngazana Basins (Beer, 1970; McLachlan *et al.*, 1976a, 1976b; McMillan, 2003a).

First described by Reuss (1863) from the middle and upper Hils clays (Barremian-Aptian) of northern Germany, *Tristix acutangula* has been recognised widely in the Early Cretaceous succession in both the Boreal and Austral realms. Espitalié & Sigal (1963b) identified *Tristix suprajurassica* in Cenozones C and D (Kimmeridgian to Early Valanginian) in the Mahajanga Basin of north-west Madagascar.

OCCURRENCE IN THE BETHELSDORP FORMATION

4798, 4901 and 11476, BSP only.

Tristix oolithica (Terquem, 1886)

Fig. 27, nos 10–11.

Tritaxia oolithica Terquem, 1886: 60, pl. 7, figs 5a–b.

Tristix oolithica (Terquem); Gordon, 1965: 849, text-figs. 8a–f; fig. 10, nos 3–4; Gordon, 1967: 454, pl. 3, fig. 14; Coleman, 1981: 123, pl. 6.2.4, figs 16–17.

REMARKS

Much variation is evident in authors' specimens referred to this name: compare the illustrations in the references listed above. In general, tests of *Tristix oolithica* are narrower, often more nearly parallel-sided, and maximum test width is at the level of the second or third from last chamber, when compared with the rapidly widening and more carinate tests of *Tristix acutangula* (Reuss). Coleman (1981) notes that it is synonymous with *Tristix suprajurassica* of Paalzow (1932). For the present study the interpretation of this species as defined by Gordon (1965) has been followed.

Some variation in the few tests referred to *Tristix oolithica* from the Bethelsdorp Formation is also evident. These are mostly non-carinate at the margins, and they compare closest to the tests illustrated as 8d and 8f of text-figure 8 of Gordon (1965). One of the Bethelsdorp Formation tests is so mildly triangular in cross-section that it appears intermediate between *Tristix* and *Nodosaria*. Both radiate and simple circular apertures are mentioned in the literature for this species. The Bethelsdorp Formation tests mostly do not show the aperture clearly: in the two tests that do, the aperture is radiate in both. These South African tests are more delicately constructed than the elongate tests of *Tristix cuneatus*, with up to eight rectilinear chambers, described by Ivanova (1973) from the Volgean of northern Siberian basins.

Tristix oolithica was first described by Terquem (1886) from the Fullers Earth ("Oolithe Inférieur") of Jelenice, near Warsaw, Poland. Bielecka & Pożaryski (1954) obtained specimens from the Astartian-Bononian (Oxfordian-Portlandian) succession of central Poland. Gordon (1965) noted the species in the Late Oxfordian Corallian beds of Dorset, and again (1967) in the Callovian Brora Argillaceous Series, Scotland. Coleman (1981) regarded its stratigraphic range as limited to the Bathonian and Callovian stages of England, but the range in Poland appears to be up to the top of the Jurassic.

OCCURRENCE IN THE BETHELSDORP FORMATION

2948' in SW 1/08; 420–423m, 462–465m, 467.0m and 467.30m in BT 1/74; not in ST 1/71 or BSP.

Tristix sp. 1

Fig. 27, nos 12–13.

REMARKS

Two tests of a distinctively ornamented *Tristix* have been found in two different samples from Bethelsdorp Salt Pan. Numerous fine vertically-aligned striations cover all three sides of one test, which otherwise is morphologically identical to tests of *Tristix acutangula*, as described above. Because of the roughness of the striations and

their irregularity, it is suspected that they are due to post-depositional calcification or dissolution of the test exterior, and are not a true surface ornamentation.

OCCURRENCE IN THE BETHELSDORP FORMATION

4798 and 11479 in BSP only.

Family VAGINULINIDAE Reuss, 1860

Subfamily LENTICULININAE Chapman, Parr & Collins, 1934

Genus LENTICULINA Lamarck, 1804

Lenticulina muensteri (Roemer, 1839) *sensu lato*

Robulina muensteri Roemer, 1839: 48, pl. 20, fig. 29.

Lenticulina (*Lenticulina*) *muensteri* (Roemer); Farinacci, 1965: 240, fig. 21.

Lenticulina muensteri (Roemer); Jendryka-Fuglewicz, 1975: 149, pl. 8; pl. 9; pl. 10; pl. 11, figs 1–6; pl. 19; pl. 20, figs 1–2.

REMARKS

Two poorly preserved examples are referred to the *Lenticulina muensteri* group, but only in a broad sense. A very detailed analysis of *Lenticulina muensteri*, apparently ubiquitous; a species which has been interpreted very widely since it was first described, has been given by Jendryka-Fuglewicz (1975), based on Polish material. Jendryka-Fuglewicz considered its stratigraphic range in Poland as Aalenian (Dogger, mid Jurassic) to Albian (Early Cretaceous).

OCCURRENCE IN THE BETHELSDORP FORMATION

2948' in SW 1/08; not in ST 1/71, nor BT 1/74, nor BSP.

Lenticulina cf. *L. quenstedti* (Gümbel) forma A Wernli, 1971

Fig. 23, no. 20.

see *Lenticulina quenstedti* (Gümbel) forma A Wernli, 1971: 322, pl. 4, figs. 23, 27; pl. 10, fig. 1.

see *Lenticulina quenstedti* (Gümbel); Morris & Coleman, 1989: 226, pl. 6.3.8, fig. 12.

REMARKS

Wernli (1971) illustrated three specimens of *Lenticulina quenstedti* forma A, derived from the Bajocian to Early Oxfordian of Switzerland, and the Jura Méridional of France (see also Wernli & Septfontaine, 1971). The two specimens from the Bethelsdorp Formation are very similar to that illustrated by Wernli (1971) as pl. 4, fig. 23. Both in the case of this specimen and our two examples, it would appear

that they are juveniles, and have not yet constructed a full whorl of chambers. As a result, the surface rib that encircles the proloculus has not yet formed a complete circle, as seen clearly in Wernli's illustration. The sutures of the South African tests are raised into low, broadly rounded ribs, and become limbate. The ribs fade towards the faintly carinate margin, and the rib encircling the proloculus is only poorly developed. The small number of tests and the absence of any adult examples in the Bethelsdorp Formation material hinder a more positive taxonomic identification, and cast uncertainty on age-determinations based on these two specimens vis-à-vis *Lenticulina quenstedti* s.s.

Lenticulina quenstedti has been widely recorded in the Tethyan Middle and Late Jurassic, as detailed by Farinacci (1965). Further south, Espitalié & Sigal (1963b) record this species as ranging through Cenozones A and B (Late Bathonian to Early Oxfordian) of the Mahajanga Basin, Madagascar.

OCCURRENCE IN THE BETHELSDORP FORMATION

2948' in SW 1/08; not in ST 1/71, BT 1/74 or BSP.

Subfamily PALMULINAE Saidova, 1981
Genus NEOFLABELLINA Bartenstein, 1948

Neoflabellina sp.

REMARKS

A single test of *Neoflabellina* was obtained from the Bethelsdorp Salt Pan outcrops. It appears to be unrelated to other Jurassic or Early Cretaceous species of this genus. The test consists of seven chambers arranged in an arc, increasing steadily in size as added, followed by two broadly arched chambers that overlie all the previous ones. The periphery of the test is broadly rounded. The sutures are initially lightly raised, later becoming slightly depressed. The aperture is terminal, apparently a circular opening, but it is damaged.

Espitalié & Sigal (1963b) described the occurrence of a number of *Neoflabellina* species from the Late Jurassic and Early Cretaceous rocks of the Mahajanga Basin in Madagascar, but all of these species possess chevron-shaped adult chambers, in contrast to the broadly arched ones of this South African test.

OCCURRENCE IN THE BETHELSDORP FORMATION

2948' in SW 1/08; 4901 in BSP.

Subfamily MARGINULININAE Wedekind, 1937

Genus ASTACOLUS de Montfort, 1808

Astacolus cf. *A. major* (Bornemann) forma A Lutze, 1960

Fig. 27, no. 14.

see *Lenticulina* (*Astacolus*) *major* (Bornemann) forma A Lutze, 1960: 454, pl. 28, figs 5a–b, text-fig. 12d–g.

see *Lenticulina major* (Bornemann); Morris & Coleman, 1989: 226, pl. 6.3.8, fig. 11.

REMARKS

A single well-preserved specimen of *Astacolus* from the Bethelsdorp Formation appears to be similar to that illustrated by Lutze (1960) under this name. Lutze considered his forma A to differ from the specimens described by Bornemann in the possession of more or less limbate sutures. The outline of the test is similar in both cases. The single specimen from the Bethelsdorp Formation exhibits strongly limbate sutures that are adjoining sutural depressions. Lutze (1960) described his specimens from Callovian and Oxfordian rocks of northwest Germany.

OCCURRENCE IN THE BETHELSDORP FORMATION

Only in 591–594m, BT 1/74.

Astacolus pellucida Said & Barakat, 1958

Fig. 27, no. 15.

Astacolus pellucida Said & Barakat, 1958: 247, pl. 3, fig. 18; pl. 5, fig. 36.

REMARKS

A few tests from Bethelsdorp Salt Pan are referable to this species. They differ slightly from the description and illustrations given by Said & Barakat (1958) in displaying slightly curved sutures in the later uncoiled portion of the test. In addition the peripheral margin is thickened and sub-rounded rather than acutely angled. This species was originally described from Callovian and Kimmeridgian rocks of northern Sinai (Said & Barakat, 1958).

OCCURRENCE IN THE BETHELSDORP FORMATION

2948' in SW 1/08; nowhere else.

Astacolus sp.
Fig. 27, no. 16.

REMARKS

A few small juvenile, unornamented *Astacolus* specimens, with weakly depressed and curved sutures, were obtained from the Bethelsdorp Formation. Lack of material prevented a specific identification. Similar conservative forms occur widely throughout the Jurassic and Cretaceous successions.

OCCURRENCE IN THE BETHELSDORP FORMATION

609–612m in BT 1/74; 1250–1255m in ST 1/71; 2948' in SW 1/08; not in BSP.

Genus MARGINULINA d'Orbigny, 1826

Marginulina declivis (Schwager, 1865)
Fig. 27, nos 17–18.

Dentalina declivis Schwager, 1865: 105, pl. 3, fig. 1.

Marginulina declivis (Schwager); Seibold & Seibold, 1956: 125, text-fig. 3, nos w–x; Hanzlíková, 1965: 82, pl. 7, figs 7a–b, 11a–b.

REMARKS

The few specimens from the Bethelsdorp Formation make a confident identification with Schwager's species difficult: in addition most of the specimens are damaged. The large number of morphologically similar species in the Jurassic to *Marginulina declivis* further complicates identification. Both Seibold & Seibold (1956) and Hanzlíková (1965) note that this species appears to be transitional between the genera *Dentalina* and *Marginulina*.

The tests from the Bethelsdorp Formation display rather more strongly inflated chambers, which are slightly less high, than are evident in the chambers of the specimen illustrated by Schwager. Rather the South African tests compare closely with one of the specimens illustrated by Hanzlíková (1965, pl. 7, figs 7a–b). *Marginulina declivis* was first described from the Impressa-ton (Early Oxfordian) of Bavaria, southern Germany, while Hanzlíková (1965) obtained specimens from the Klentnice beds (latest Oxfordian to Kimmeridgian) of the Czech Republic.

OCCURRENCE IN THE BETHELSDORP FORMATION

2866', 2948' in SW 1/08; 1400m in ST 1/71; not in BSP or BT 1/74.

Marginulina spp.

REMARKS

A small number of badly preserved *Marginulina* specimens were encountered in the Bethelsdorp Formation, but none of them proved distinctive enough to be identified to species level.

OCCURRENCE IN THE BETHELSDORP FORMATION

11476 in BSP; 420–423m in BT 1/74; not in ST 1/71 or SW 1/08.

Genus VAGINULINOPSIS Silvestri, 1904

Vaginulinopsis spp.

Fig. 27, nos 19–20.

REMARKS

Several *Vaginulinopsis* tests, all of single specimens of different species. One is characterised by a strongly compressed test and low chambers. It is thus clearly distinct from *Vaginulinopsis vetusta* (d'Orbigny) or *Vaginulinopsis matutina* (d'Orbigny) and other similar forms. Another test is much closer to *Vaginulinopsis matutina* (d'Orbigny).

OCCURRENCE IN THE BETHELSDORP FORMATION

11477 in BSP only.

Subfamily VAGINULININAE Reuss, 1860

Genus CITHARINA d'Orbigny, 1839

Citharina harpa (Roemer, 1841)

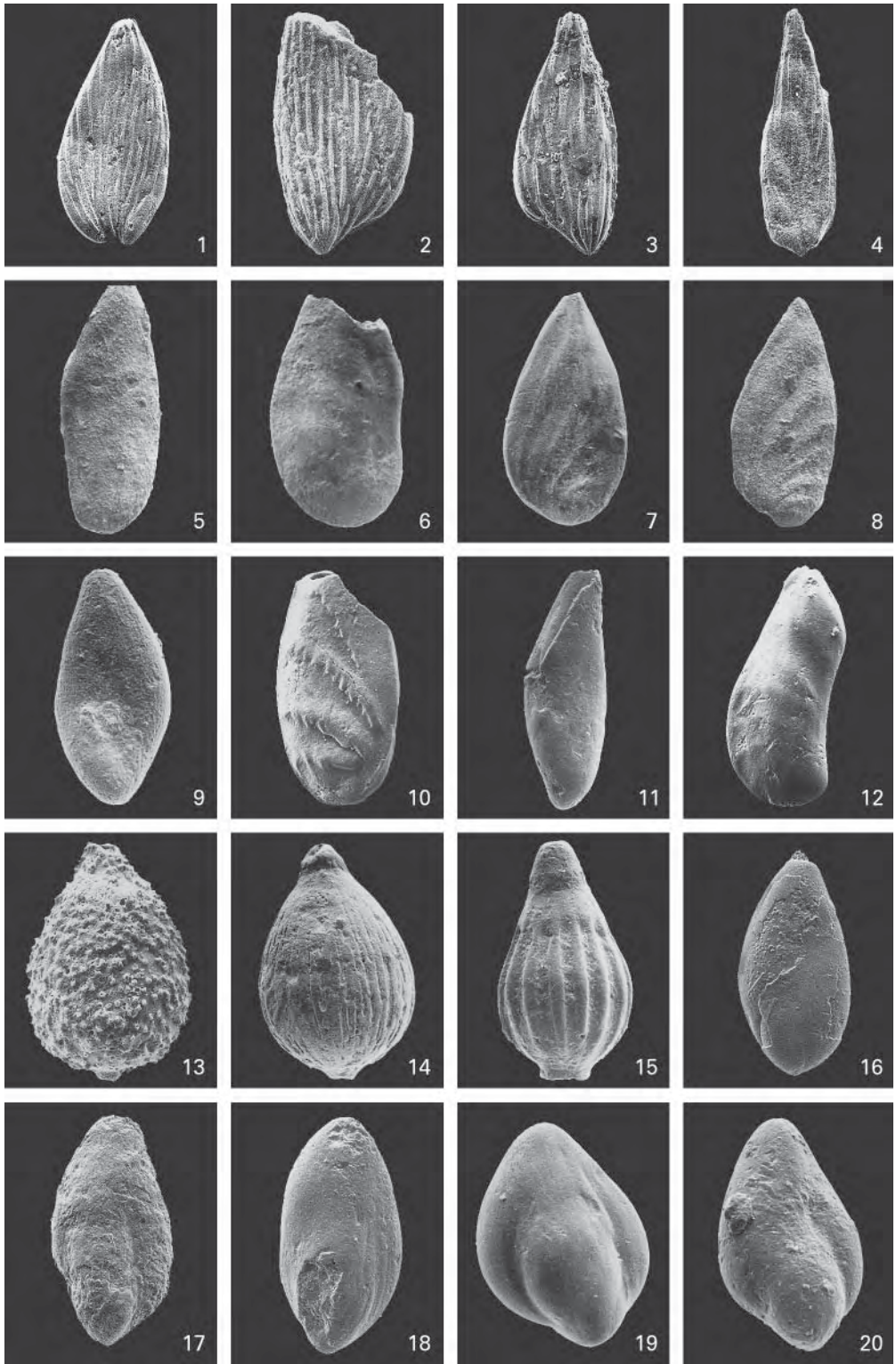
Fig. 28, no. 1.

Vaginulina harpa Roemer, 1841: 96, pl. 15, fig. 13; Neaverson, 1921: 463, pl. 9, fig. 7; Cifelli, 1959: 322, pl. 5, figs 18–19.

Citharina harpa (Roemer); Bartenstein & Kaever, 1973: 223, pl. 2, figs 21–23; pl. 6, fig. 104.

REMARKS

Since Roemer (1841) first described and illustrated this species, authors have varied in its interpretation, particularly in the nature and degree of the surface ornamentation, and in the outline of the test. Roemer figured a test with surface ornament of vertically-aligned ribs that extend without interruption up the full height of the test. Later authors have illustrated tests featuring shorter, more irregular ribs



interspersed with the long ribs. Cordey (1962) has regarded some Jurassic records to this species, such as by Macfadyen (1935) and Bartenstein & Brand (1937), as being more correctly referable to *Citharina flabellata* (Gümbel). Bartenstein & Brand show examples with bifurcating ribs (1937, pl. 14B, fig. 7; pl. 15A, fig. 24a–b; pl. 15B, figs. 12b, d), and these are probably referable to *C. flabellata*. However, other tests illustrated by Bartenstein & Brand (1937, pl. 14C, fig. 10; pl. 15B, figs. 12a and c) show either no bifurcating nor irregular ribs, or only rare bifurcations in the earliest part of the test. These latter three tests illustrated by Bartenstein & Brand (1937) are regarded as falling within the confines of *Citharina harpa* (Roemer). *Citharina pseudostriatula* Bartenstein & Brand is similarly different from *Citharina harpa* (see McMillan, 2003a: 149, figs 48M–N and 49A–B), especially in its more delicate ribbing pattern.

Citharina harpa was originally described from the Early Cretaceous Hilston of northwestern Germany. Late Jurassic records include: Neaverson (1921) from the Kimmeridgian Hartwell Clay; Cifelli (1959) from the Bathonian sediments of southern England; Bartenstein & Brand (1937) from Callovian to Early Oxfordian sediments of north-west Germany. Early Cretaceous records include: Fletcher (1973) from the Early to Late Hauterivian portion of the Speeton Clay of Yorkshire, England; Bartenstein & Bettenstaedt (1962) indicated its range as Late Valanginian to Early Barremian in north-west Germany; Bartenstein & Kaever (1973) identified it from the Late Hauterivian rocks of Heligoland in the North Sea.

FIGURE 28 (*facing page*)

1. *Citharina harpa* (Roemer). SAM-PQ-MF-2291. BSP 11477, F1339, side view. $\times 133$.
- 2–3. *Citharina inconstans* (Terquem). 2. SAM-PQ-MF-2292. BSP 11477, F1345, side view. $\times 150$.
3. SAM-PQ-MF-2293. BSP 11477, F1347, side view. $\times 146$. 4. *Citharina* sp. SAM-PQ-MF-2294. SW 1/08, 2100'. F1324, side view. $\times 85$.
- 5–6. *Planularia beierana* (Gümbel). 5. SAM-PQ-MF-2295. BSP 4901, F1351, side view. $\times 68$. 6. SAM-PQ-MF-2296. BSP 4798, F1352, side view. $\times 82$.
- 7–8. *Planularia madagascariensis* Espitalié & Sigal. 7. SAM-PQ-MF-2297. BSP 4901, F1369, side view. $\times 89$. 8. SAM-PQ-MF-2298. BSP 4798, F1368, side view. $\times 95$.
- 9–10. *Planularia* sp. 9. SAM-PQ-MF-2299. SW 1/08, 2948'. F1356, side view. $\times 150$. 10. SAM-PQ-MF-2300. BSP 11476, side view. $\times 150$.
11. *Vaginulina* cf. *V. anomala* Blake. SAM-PQ-MF-2301. BT 1/74, 591–594m. F1355, side view. $\times 188$.
12. *Vaginulina barnardi* Gordon. SAM-PQ-MF-2302. BSP 11478, F1343, side view. $\times 145$.
13. *Lagena algoensis* McMillan. SAM-PQ-MF-2303. BSP 11477, F1342, side view. $\times 183$.
14. *Lagena* cf. *L. striatifera* Tappan. SAM-PQ-MF-2304. SW 1/08, 2866'. F1357, side view. $\times 156$.
15. *Lagena* cf. *L. sulcata* (Walker & Jacob). SAM-PQ-MF-2305. SW 1/08, 2948'. F1358, side view. $\times 165$.
- 16–18. *Eoguttulina anglica* Cushman & Ozawa. 16. SAM-PQ-MF-2306. BT 1/74, 600–603m. F1331, side view. $\times 165$.
17. SAM-PQ-MF-2307. ST 1/71, 1200–1205m. F1332, side view. $\times 182$.
18. SAM-PQ-MF-2308. ST 1/71, 1190–1195m. F1333, side view. $\times 182$.
- 19–20. *Eoguttulina liassica* (Strickland). 19. SAM-PQ-MF-2312. BT 1/74, 420–423m. F1297, side view. $\times 113$.
20. SAM-PQ-MF-2313. SW 1/08, 2100'. F1298, side view. $\times 132$.

OCCURRENCE IN THE BETHELSDORP FORMATION

11475, 11476 and 11477 in BSP; nowhere else.

Citharina inconstans (Terquem, 1868)

Fig. 28, nos 2–3.

Marginulina inconstans Terquem, 1868: 66, pl. 2, figs 1–12.

Vaginulina inconstans (Terquem); Bartenstein & Brand, 1937: 164, pl. 10, fig. 26.

Citharina inconstans (Terquem); Said & Barakat, 1958: 262, pl. 5, fig. 24.

REMARKS

Authors since Terquem have tended to regard the nine varieties (varieties A to I) initially proposed by Terquem (1868) as being not regular enough to warrant varietal names. The test wall of this species is ornamented with elongate ribs, most of which are about half the test height or more in extent. Irregularities of the ribs, such as bifurcating or sinuous ribs, occur only rarely. To some degree this ornamentation pattern appears intermediate between that of *Citharina harpa* (Roemer) on the one hand, and that of *Citharina sparsicostata* (Reuss) on the other. Terquem (1868) described this species from the Fuller's Earth (Bathonian) of Fontoy, France. Bartenstein & Brand (1937) noted it from the Early Dogger (Bajocian) sediments of north-west Germany, and Said & Barakat (1958) identified it in the Kimmeridgian rocks of Gebel Maghara, Sinai, Egypt.

OCCURRENCE IN THE BETHELSDORP FORMATION

11475, 11476, 11477 in BSP; nowhere else.

Citharina sp.

Fig. 28, no. 4.

see *Citharina austroafricana* McMillan, 2003a: 153, figs 49C–J.

see *Citharina* cf. *austroafricana* McMillan; Simeoni, 2000: 119, pl. 38, figs 5–8, text-fig.

REMARKS

McMillan (2003a) described *Citharina austroafricana* as an endemic, widespread but never common new species ranging from early Valanginian to Early Barremian rocks in the Pletmos, Gamtoos, Algoa and Mngazana Basins of South Africa. There may be records of the same species across the Jurassic–Cretaceous boundary (Vaca Muerta succession) in the Neuquen Basin in Argentina (Simeoni, 2000).

In the basal Bethelsdorp Formation (Portlandian), a different species of *Citharina* occurs rarely in the three studied borehole sections and a little more commonly in

the outcrop samples from Bethelsdorp Salt Pan. These occasional *Citharina* tests have all been found with only the initial few chambers surviving and the later chambers missing. These damaged tests feature elongate surface ribs extending over three or four chambers, over the proloculus and close to the dorsal margin, a feature also seen in tests of *Citharina austroafricana* (see McMillan, 2003a, p. 155). However, the Bethelsdorp tests otherwise differ markedly from *C. austroafricana* in that the delicate short surface ribs extend over the entire surface of each chamber, but no further. In contrast, the surface ribs of *Citharina austroafricana* are limited to the upper half or third of the chamber height, with the lower portion of each chamber devoid of all surface ribbing. It is felt that this Bethelsdorp form warrants a new species name, but the poor preservation of these tests precludes this for now. In both the Bethelsdorp Formation and the Sundays River Formation *Citharina* species appear most common in shallow-water, normal marine, clayey or silty sea-floor environments.

OCCURRENCE IN THE BETHELSDORP FORMATION

2100' in SW 1/08; 357–360m in BT 1/74; 4901, 11475, 11476, 11477 and 11479 in BSP; not in ST 1/71.

Genus PLANULARIA Defrance, 1826

Planularia beierana (Gümbel, 1862)

Fig. 28, nos 5–6.

Marginulina beierana Gümbel, 1862: 221, pl. 3, figs 20a–b.

Lenticulina (*Planularia*) *beierana* (Gümbel); Seibold & Seibold, 1955: 106, pl. 13, fig. 7, text-figs 4e–f; Seibold & Seibold, 1956: 112, text-figs 5e–h, o, p, u; Munk, 1978: 47, pl. 5, fig. 4.

Planularia beierana (Gümbel); Cordey, 1962: 380, pl. 46, fig. 11, text-figs 10–16; Winter, 1970: 33, pl. 4, fig. 119, text-figs 25a–c.

REMARKS

This species is one of a number of very closely-related ones that show features, to varying degrees, of the genera *Vaginulina*, *Astacolus*, *Planularia*, *Vaginulinopsis* and other related genera. There appears to be overlap between a number of closely related species in this group in the Jurassic and Early Cretaceous. Authors have acknowledged the wide degree of variation that tests of *Planularia beierana* exhibit. Most recent authors have been reliant on Seibold & Seibold's (1955, 1956) re-appraisals of Gümbel's (1862) and Schwager's (1865) foraminifera assemblages. Cordey (1962) has attempted to plot out the complex taxonomic history of the species.

The Bethelsdorp Formation tests are allocated, with some misgivings, in *Planularia beierana*. The South African tests appear to be more elongate-ovate in cross-section,

rather than the more strongly compressed cross-section of the test originally illustrated by Gümbel (1862). Most of the Bethelsdorp Formation tests feature parallel sides, and in none of the tests do the later chambers reach back towards the proloculus (as featured by Seibold & Seibold, 1956, text-figs 5o–p; Cordey, 1962, text-figs 10–11; Winter, 1970, pl. 4, fig. 119, text-figs 25b–c).

An additional complexity has been the apparent gradation from morphologies typical of *Planularia beierana* to those typical of *Vaginulina barnardi* Gordon. In a different direction of gradational change (notably an increase in degree of compression of test; development of pronounced backwards-extending chambers) Winter (1970) considered *Planularia madagascariensis* Espitalié & Sigal to be partly synonymous with *Planularia beierana*. These two species have been regarded as discrete in the present study.

Gümbel (1862) originally described this species from the Oxfordian Schwammmergeln of southern Germany. Most subsequent records are from the Late Jurassic succession, such as Cordey (1962), who described it as occurring in the Oxfordian of the Isle of Skye, Scotland, and Winter (1970), who identified it in the Kimmeridgian of southern Germany.

OCCURRENCE IN THE BETHELSDORP FORMATION

4798, 4901, 4904, 11475, 11476, 11477 in BSP; nowhere else.

Planularia madagascariensis Espitalié & Sigal, 1963

Fig. 28, nos 7–8.

Planularia madagascariensis Espitalié & Sigal, 1963b: 28, pl. 6, figs 8–11; pl. 34; Simeoni, 2000: 86; 125, pl. 38, fig. 14; McMillan, 2003a: 184, figs 56G–L; 57A–D.

REMARKS

See analysis of this species by McMillan (2003a, pp. 184 to 187), as occurring in the Late Valanginian to latest Hauterivian Sundays River Formation succession in the Algoa Basin. Tests of *Planularia madagascariensis* in the Bethelsdorp Formation of the onshore Uitenhage Trough show no clear differences from those in the Sundays River Formation.

Espitalié & Sigal (1963b) note in their original diagnosis for this species that one of its characteristics is a great variability in the general morphology of the test, the form of the chambers, and the intensity and distribution of surface ornamentation. In view of this, they considered *Planularia madagascariensis* to constitute a plexus of closely similar forms. In their description, they note the presence of a regularly curved keel on the dorsal margin. Tests from the Bethelsdorp Formation exhibit

keels that vary from prominent to almost absent. The surface ornamentation, described by Espitalié & Sigal as “courtes rides peu élevées, obliques par rapport au bord dorsal”, is apparent on only a few specimens from the Bethelsdorp Formation, and even then only on the final two chambers of the test.

On plate 34, Espitalié & Sigal (*op. cit.*) display morphological differences apparent in tests recovered from rocks of different ages. Of the tests illustrated, the Bethelsdorp Formation specimens are closest to fig. 2 (from Cenozone B, Late Callovian to Early Oxfordian) and fig. 11 (Cenozone C supérieure, Kimmeridgian to Early Portlandian). Espitalié & Sigal (1963b) reported the stratigraphic range of *Planularia madagascariensis* in the Mahajanga Basin of Madagascar as being Late Callovian to Early Valanginian (Cenozones B to D). Very closely similar forms occur in the Vaca Muerta Formation (Portlandian-Berriasian) of the Neuquén Basin, Argentina (Simeoni, 2000). In South Africa its full stratigraphic range is Portlandian to later Barremian (McLachlan *et al.*, 1976a, b; McMillan, 2003a).

OCCURRENCE IN THE BETHELSDORP FORMATION

3023' in SW 1/08; 4798, 4901, 11475, 11476, 11477 and 11479 in BSP; not in BT 1/74 or ST 1/71.

Planularia spp.
Fig. 28, nos 9–10.

REMARKS

Four specimens of either poorly preserved or indistinguishable *Planularia* tests were encountered in the course of this study. The most distinctive of these tests is illustrated, but none of them could be identified to specific level.

OCCURRENCE IN THE BETHELSDORP FORMATION

2948' in SW 1/08; 591–594m in BT 1/74; 11476 in BSP; not in ST 1/71.

Genus VAGINULINA d'Orbigny, 1826

Vaginulina cf. *V. anomala* Blake, 1876
Fig. 28, no. 11.

see *Vaginulina anomala* Blake, 1876: 464, pl. 17, figs 23, 23a.

REMARKS

A small number of juvenile tests are similar to the specimens of *Vaginulina anomala* illustrated by Gordon (1967) from the Callovian Brora Argillaceous Series of the

east coast of Scotland. The juvenile tests from the Bethelsdorp Formation are insufficient to fully confirm the identification.

OCCURRENCE IN THE BETHELSDORP FORMATION

467.0m, 591–594m in BT 1/74; not in ST 1/71, SW 1/08 nor BSP.

Vaginulina barnardi Gordon, 1965

Fig. 28, no. 12.

Vaginulina barnardi Gordon, 1965: 852, text-fig. 7, nos 24–25; text-fig. 9a–f; Shipp & Murray, 1981: 142, pl. 6.3.4, fig. 17.

REMARKS

Specimens very similar in test morphology to *Vaginulina barnardi* Gordon (1965) were obtained in some numbers from the samples collected at Bethelsdorp Salt Pan. These tests compare closely with Gordon's original specimens and original description, especially in the manner of chamber growth in the early part of the test. Some tests from the Bethelsdorp Formation develop a more sub-angular or faintly thickened dorsal margin than is usual, although more commonly this margin is sub-rounded or rounded. The style of variation depicted in *Vaginulina barnardi* by Gordon (1965) in his text-fig. 9a–f, is similar to the variation evident in the present material. The major difference between the two groups of tests, however, is the complete absence of the surface “ornamentation of fine longitudinal striations” described by Gordon (1965, p. 853) as occurring on the test surface of his English specimens. Shipp & Murray (1981) describe these fine striations as being exceptionally elongate, always present, but often very faint.

Tests of *Vaginulina barnardi* may on occasion approach the test morphology of *Vaginulinopsis prima* (d'Orbigny) specimens encountered in the Sundays River Formation (McLachlan *et al.*, 1976a; McMillan, 2003a). In addition, Gordon included several earlier references to *Vaginulina legumen* (non Linné) as synonymous with *Vaginulina barnardi*. Gordon (1965) first described the species from the Oxfordian of southern England (also see Shipp & Murray, 1981).

OCCURRENCE IN THE BETHELSDORP FORMATION

4798, 4901, 4904, 11475, 11476, 11477, 11478, 11479 in BSP; nowhere else.

Vaginulina spp.

REMARKS

A few damaged and corroded specimens have been referred to the genus *Vaginulina*, but none of them could be identified to species level.

OCCURRENCE IN THE BETHELSDORP FORMATION

2948' in SW 1/08; 11477 in BSP; nowhere else.

Family LAGENIDAE Reuss, 1862

Genus LAGENA Walker & Jacob, in Kanmacher, 1798, *sensu lato*

Lagena algoaensis McMillan, 2003

Fig. 28, no. 13.

Lagena algoaensis McMillan, 2003a: 163, figs 51C–J.

REMARKS

A small number of *Lagena* specimens with a tuberculate surface ornamentation were obtained from the outcrop samples at Bethelsdorp Salt Pan. These specimens have been referred to *Lagena algoaensis* in preference to *Lagena oxystoma* Reuss, since the latter species is characterised by an exclusively hispid ornamentation, a feature not seen in the Bethelsdorp Formation tests. All of these Bethelsdorp Salt Pan tests possess short apertural necks, and a short, blunt apical projection. The density of the surface ornamentation varies from specimen to specimen. However, all tests are truly tuberculate, and contrast with the rather more rugose ornamentation of *Lagena apiculata neocomiana* Bartenstein & Brand. On the basis of the ornamentation, this species does not fit well in any of the presently erected lagenid genera, and certainly falls outside the range of *Reusoolina* Colom, 1956; and so for the moment is retained in the genus *Lagena*.

Lagena algoaensis ranges from Late Valanginian Biozone Bb to Late Hauterivian Biozone I in the Sundays River Formation (McMillan, 2003a), but the species is rare elsewhere in the South African Cretaceous basins.

OCCURRENCE IN THE BETHELSDORP FORMATION

4798, 11475, 11477 in BSP only.

Lagena cf. *L. striatifera* Tappan, 1940
Fig. 28, no. 14.

see *Lagena striatifera* Tappan, 1940: 112, pl. 17, figs 18a–b; Tappan, 1943: 504, pl. 80, figs 32a–b.

REMARKS

A single test of *Lagena* from the SW 1/08 borehole section may prove to be referable to *Lagena striatifera*, originally described from the Albian and Cenomanian of Texas and Oklahoma (Tappan, 1940, 1943). This species was originally described as being ornamented with “about 28 fine, low ribs”. However, the test from the Bethelsdorp Formation displays more irregular, and distinctly more numerous ribs than does Tappan’s Cretaceous species. The aperture of *Lagena striatifera* is developed on a fairly long tubular neck, whereas that from the Bethelsdorp Formation is on a shorter neck, although it seems that the neck has been damaged. In most other respects, the two forms appear similar. This species is a true *Lagena*.

OCCURRENCE IN THE BETHELSDORP FORMATION

Only at 2866', SW 1/08.

Lagena cf. *L. sulcata* (Walker & Jacob, 1798)
Fig. 28, no. 15.

see *Lagena sulcata* Lofaldli & Thusu, 1979: 421, pl. 46, fig. 19 (*non* Walker & Jacob).

see *Lagena sulcata* s.l. Musacchio, 1979: 258, pl. 4, fig. 23 (*non* Walker & Jacob).

see *Lagena* sp. 3 Jones & Wonders, 1992: 563, pl. 2, fig. 9.

see *Oolina* cf. *sulcata* (Walker & Jacob); Holbourn & Kaminski, 1997: 75, pl. 44, figs 8a–b, 9.

see *Lagena alexandria* McMillan, 2003a: 161, figs 50H–L.

REMARKS

Again from the Bethelsdorp Formation of the SW 1/08 borehole section, this single specimen of *Lagena* is ornamented with 15 vertically aligned ribs. The surface ornament consists of broadly rounded ribs that appear near the apical projection and disappear some way from the aperture at the base of the conical neck, where the intervening grooves are abruptly terminated. The test displays a broad, blunt apical projection, and the aperture is developed on a rather conical neck. The apertural neck is smooth and unornamented. The style of surface ornamentation is distinctive, and is unlike other Late Jurassic or Early Cretaceous species of *Lagena*.

OCCURRENCE IN THE BETHELSDORP FORMATION

2948' in SW 1/08 only.

Family POLYMORPHINIDAE d'Orbigny, 1839

Subfamily POLYMORPHININAE d'Orbigny, 1839

Genus EOGUTTULINA Cushman & Ozawa, 1930

REMARKS

The three studied deep borehole sections through the Bethelsdorp Formation of the onshore portion of the Uitenhage Trough all yielded foraminifera assemblages in which specimens of *Eoguttulina* are very numerous at some horizons. The large numbers of individuals of a genus that possesses relatively few distinctive specific features has proven difficult to satisfactorily speciate. Lloyd (1962), in his discussion of *Eoguttulina*, noted the occurrence of "suites of specimens from the Kimmeridge Clay, showing little variation in other characters, differed in their chamber arrangements to a far greater extent than in any post-Jurassic genus (as recorded in the literature)". Lloyd employed the following features in the distinction of species of *Eoguttulina*:

1. Test shape in lateral (side) view.
2. Amount of overlap of later chambers on earlier ones.
3. Flush or depressed sutures.
4. Relationship of adjacent chambers.
5. Nature of surface of test, particularly size and disposition of pores.

Lloyd (1962) considered that variations of total numbers of chambers, of the form of the aperture, and of the shape and size of the proloculus showed little distinctive change between species. These various features have been followed when examining tests of *Eoguttulina* from the Bethelsdorp Formation. However, segregation of the various species remains difficult, primarily because of continuous variation of Lloyd's five features throughout all of the studied specimens. Each test must be examined individually. The preservation of tests in the Bethelsdorp Formation also causes difficulties, since most tests possess fairly thin test walls that are frequently damaged, particularly in the case of tests with a filling of framboidal pyrite. Because of variations in chamber arrangement and damaged specimens, it also frequently proved not possible to establish whether specimens of *Globulina prisca* Reuss were truly referable to that genus, or were rather juvenile individuals of *Eoguttulina*. In such cases test shape and size have been employed, so that there is probably an excessive number of *Globulina prisca* specimens listed on the borehole range charts.

No polymorphinids encountered in the samples studied from the Bethelsdorp Formation are distinguished by a fistulose final chamber; and no attached forms were found (such as the test illustrated by Lloyd, 1962, as plate 1, fig. 11a-b). Lloyd considered that the variability both of the chamber arrangement and of the form of the test, were aspects of the "primitiveness of *Eoguttulina*". From this study, it would rather be argued that this variability results from inhabiting more

than usually stressful environments. The Kimmeridge Clay, rich in organic debris, is characterised by dysaerobic depositional environments, and is similar in some respects to the Bethelsdorp Formation. Ioannides *et al.* (1976) considered that most of the sapropelic material in the Kimmeridge Clay is land-derived, principally from swampy vegetation. Probably similar conditions existed on the land-margins encircling deposition of the Bethelsdorp Formation, leading in both cases to acidic (low pH), oxygen-poor environments, and a tendency towards accumulation of organic-rich, high-gamma, unusually fine-grained claystones on the sea-floor: an ideal setting for the generation of pyrite.

Eoguttulina anglica Cushman & Ozawa, 1930

Fig. 28, nos 16–18.

Eoguttulina anglica Cushman & Ozawa, 1930: 16, pl. 1, figs 3a–c; Ten Dam, 1948: 186; Lloyd, 1962: 374, pl. 1, figs 10a–c; Neagu, 1965: 28, pl. 7, figs 1–2; McLachlan *et al.*, 1976b: 333, fig. 16, no. 28; McMillan, 2003a: 211, figs 62N–O; 64A–B.

REMARKS

Tests referred to *Eoguttulina anglica* compare closely with those previously encountered in the Mngazana beds (McLachlan *et al.*, 1976b) and the Sundays River Formation of the Algoa Basin (McMillan, 2003a). The species is characterised by elongate, rather inflated chambers, particularly in the later part of the test, where the final two chambers embrace much of the test (usually about $\frac{2}{3}$ of the test). The sutures are depressed. Tests from the Bethelsdorp Formation compare fairly closely with the original description and illustrations of *Eoguttulina anglica* given by Cushman & Ozawa (1930), but many of the South African specimens exhibit not quite so inflated chambers as the described holotype. Cushman & Ozawa (1930) described this species from the Cambridge Greensand (Cenomanian) of eastern England. Neagu (1965) noted it from the Albion of Rumania, while Lloyd (1962) reported it from the type Kimmeridgian of Dorset, England.

OCCURRENCE IN THE BETHELSDORP FORMATION

357–360m, 420–423m, 456 to 467.3m, 492–495m, 510–513m, 591 to 612m in BT 1/74; 1170 to 1415m in ST 1/74; 2090 to 3023' in SW 1/08; 11479 in BSP.

Eoguttulina cf. *E. inovroclaviensis* (Bielecka & Pożaryski, 1954)

Fig. 29, nos 2–4.

see *Sigmomorphina inovroclaviensis* Bielecka & Pożaryski, 1954: 63, 192, pl. 9, figs 47a–c. *Eoguttulina inovroclaviensis sensu* Lloyd, 1962: 372, pl. 1, figs 7a–c, text-figs 4A–B (*non* Bielecka & Pożaryski).

Eoguttulina cf. *E. inovroclaviensis* (Bielecka & Pożaryski); McLachlan *et al.*, 1976b: 333, fig. 17, no. 1; McMillan, 2003a: 212, figs 63A–C.

REMARKS

Early Cretaceous records of this distinctive *Eoguttulina* in South Africa have previously been commented on (McLachlan *et al.*, 1976b; McMillan, 2003a), but the species is more frequent in the Portlandian Bethelsdorp Formation, although it is never the dominant polymorphinid. These tests are similar to *Eoguttulina inovroclaviensis* (Bielecka & Pożaryski), but not exactly the same. The Polish species displays very elongate, strongly overlapping and rather inflated chambers, a moderately compressed test, with an ovate cross-section to the test. Basing his remarks partly on the original Polish specimens, and partly on his type Kimmeridge Clay specimens, Lloyd (1962) noted that the later chambers are nearly opposed, and although this arrangement is similar to that in *Sigmomorphina*, the earlier chambers are arranged in a “typically eoguttuline” manner. There thus seems to be no doubt that this is an *Eoguttulina*, but it is not typical of the genus.

The southern African tests, from the Late Valanginian Mngazana beds (McLachlan *et al.*, 1976b), the Late Valanginian to Hauterivian Sundays River Formation (McMillan, 2003a), and from the Portlandian Bethelsdorp Formation, all differ from Polish specimens in the size and degree of inflation of the final chambers. Southern African tests possess larger, more inflated and more embracing last-formed chambers than do the Polish tests. Other features between the two are very similar: in both, the last-formed chambers are almost opposing, and they extend back almost to the proloculus. Many southern African specimens also exhibit the distinct recessed “step” in the outline of the test, at the base of the final two chambers. In consequence, all three southern African records of this distinctive polymorphine morphology are regarded as similar to, but not the same as *Eoguttulina inovroclaviensis* (Bielecka & Pożaryski), and very much closer to Lloyd’s interpretation of the species.

Bielecka & Pożaryski (1954) described the species from Kimmeridgian and Portlandian (Bononian) rocks of central Poland. Lloyd’s specimens were from the type Kimmeridgian of Dorset, England.

OCCURRENCE IN THE BETHELSDORP FORMATION

2100 to 2140', 2795', 2948' in SW 1/08; 1170 to 1180m, 1250–1255m, 1270–1275m, 1380–1385m in ST 1/71; 366 to 467.3m, 510–513m in BT 1/74; not in BSP.

Eoguttulina liassica (Strickland, 1846)

Fig. 28, nos 19–20. Fig. 29, no. 1.

Polymorphina liassica Strickland, 1846: 31, text-fig. b.

Eoguttulina liassica (Strickland); Bielecka & Pożaryski, 1954: 64, 193, pl. 10, figs 49a–b; Tappan, 1955: 83, pl. 28, figs 17–19; Lloyd, 1962: 370, pl. 1, figs 1–3, text-figs 2A–E; Gordon, 1965: 858, text-fig. 10, nos 16–18; Bielecka, 1975: 352, pl. 10, figs 10–11.
see *Eoguttulina* cf. *E. liassica* (Strickland); McLachlan *et al.*, 1976b: 333, fig. 16, no. 27; McLachlan *et al.*, 1976a: 358, fig. 13, no. 8; McMillan, 2003a: 213, figs 64C–E.

REMARKS

This is a widespread and common species especially in the Jurassic. Strickland (1846) illustrated only one magnified view of the species and gave only a very short description, but this is complemented by Lloyd's (1962) detailed study of *Eoguttulina liassica*, as encountered in the Kimmeridge Clays of southern England. Lloyd recognised two forms: group A featuring elongate tests, and similar to Strickland's original type, while group B are shorter and broader tests, with particularly large final chambers that extend back almost to the proloculus of the test. Individuals typical of both groups occur in the Portlandian Bethelsdorp Formation, but the more globular, megalospheric tests of group B are much the more distinctive, and these have been emphasised in previous southern African studies. Tests of group A are morphologically close to *Eoguttulina anglica* Cushman & Ozawa.

Strickland (1846) described this species from near the base of the Lias succession at Cleeve Bank, near Evesham, England, while later authors have reported it from throughout the Jurassic succession of Europe, and occasional reference has been made to it from elsewhere.

OCCURRENCE IN THE BETHELSDORP FORMATION:

1170 to 1455m in ST 1/71; 2040 to 3023' in SW 1/08; 357 to 468.0m, 474–477m, 591 to 612m in BT 1/74; not in BSP.

Eoguttulina cf. *E. metensis* (Terquem, 1864)

Fig. 29, no. 5.

see *Polymorphina metensis* Terquem, 1864: 301, pl. 13, figs 38a–b.

see *Eoguttulina metensis* (Terquem); Lloyd, 1962: 373, pl. 1, figs 6a–c, text-figs 6A–B.

REMARKS

A few, very poorly preserved specimens from the Bethelsdorp Formation may be referable to *Eoguttulina metensis*. They display the same characteristics as described by Lloyd (1962) for this species, particularly in the outline of the test, the arrangement

of the chambers (and especially in the relationship of the final two chambers to the chambers in the rest of the test), and in the slight overlap of chambers over those of the previous whorl. The narrow, depressed sutures described by Lloyd are not apparent in the South African tests. For both this reason and the poor preservation it appears best to consider these tests as *Eoguttulina* confer *metensis*, for the time being.

OCCURRENCE IN THE BETHELSDORP FORMATION

467.3m in BT 1/74; 2100' in SW 1/08; neither in ST 1/71 nor BSP.

Eoguttulina oolithica (Terquem, 1874)

Fig. 29, no. 6.

Polymorphina oolithica Terquem, 1874: 299, pl. 32, figs 1–10; Kuhn, 1936: 450, text-fig. 12.
Eoguttulina oolithica (Terquem); Bizon, 1958: 17; Bielecka, 1960a: 83, 143, pl. 7, fig. 61;
 Cordey, 1962: 392, pl. 48, fig. 36; Lloyd, 1962: 373, pl. 1, figs 5 and 8, text-figs 5A–B.

REMARKS

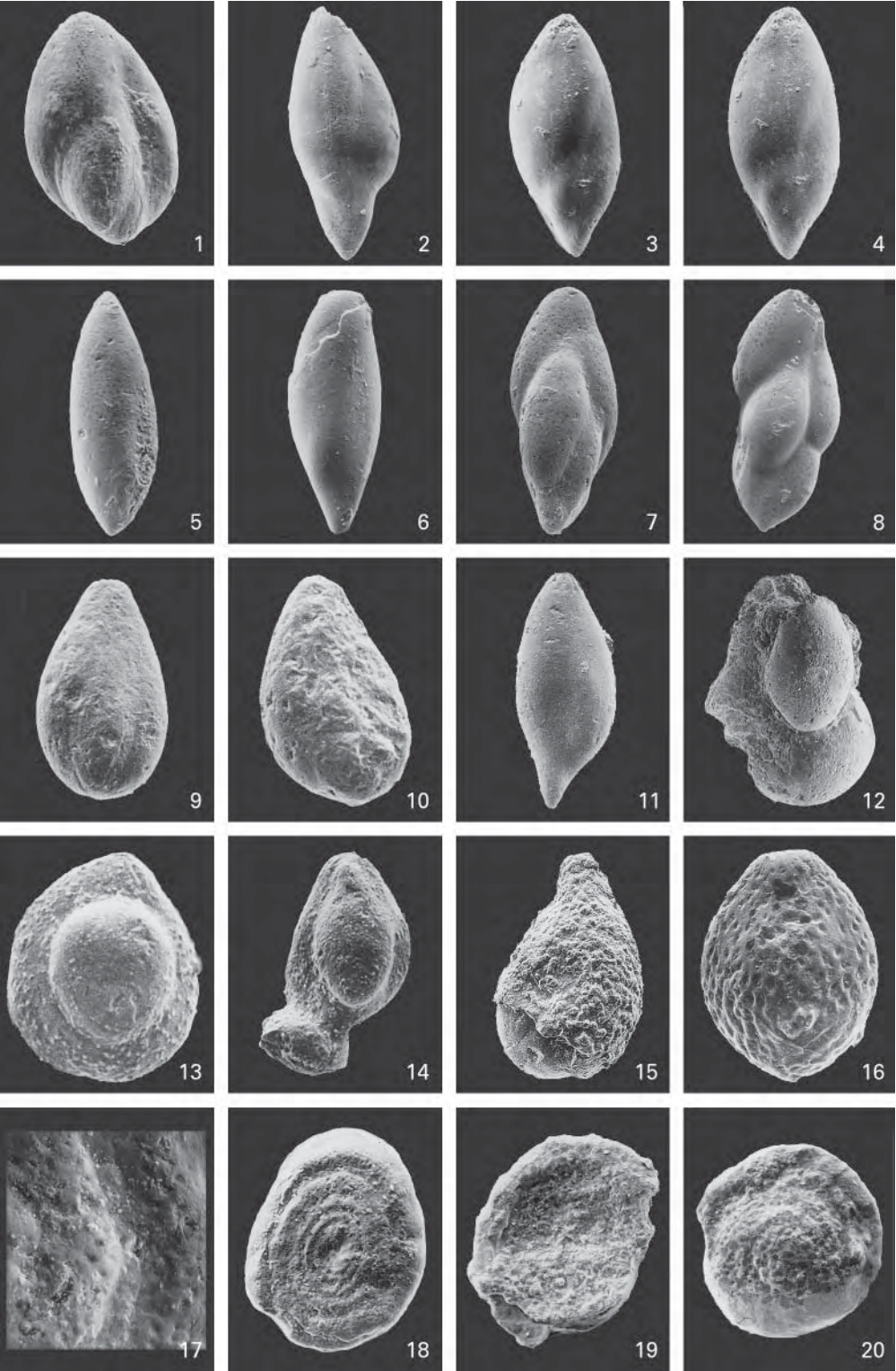
Terquem (1874) illustrated a variety of forms in his original description of this species. Those forms with a non-inflated, elongate-ovate test have been considered characteristic of *Eoguttulina oolithica* by later authors. The regular, non-lobate outline to the test is this species' most distinctive feature. The later chambers usually extend back as far as the initial portion of the test. Only a small number of specimens were found in the Bethelsdorp Formation, but they are typical in all respects. Test outlines of some are more elongate and spindle-shaped, whereas others are more typically elongate-ovate.

Terquem (1874) obtained specimens from the Bajocian-Bathonian rocks of the Moselle departement of France; similarly, most later records of *Eoguttulina oolithica* are from the Middle to Late Jurassic succession of north-west Europe. Bielecka (1960a) noted the species as occurring in the Callovian to Oxfordian of southern Poland, Bizon (1958) obtained it from the Oxfordian of Villiers-sur-Mer, northern France, Cordey (1962), from the Oxfordian of the Isle of Skye, Scotland, and Lloyd (1962) described the species in some detail based on material from the type Kimmeridgian of Dorset, England.

A similar form to *Eoguttulina oolithica* has been illustrated by Espitalié & Sigal (1963b) as *Globulina* aff. *oolithica*, from the later Jurassic of the Mahajanga Basin, Madagascar.

OCCURRENCE IN THE BETHELSDORP FORMATION

2100' in SW 1/08; 1170–1175m in ST 1/71; 339–342m, 420–423m, 467.0 to 467.30m, 609–612m in BT 1/74; not in BSP.



Eoguttulina polygona (Terquem, 1864)

Fig. 29, nos 7–8.

Polymorphina polygona Terquem, 1864: 305, pl. 14, figs 16–41.*Eoguttulina* cf. *E. polygona* (Terquem); Said & Barakat, 1958: 263, pl. 1, fig. 35; pl. 3, fig. 37; pl. 5, fig. 39.*Eoguttulina polygona* (Terquem); Lloyd, 1962: 372, pl. 1, fig. 4, text-figs 3A–C; Bielecka, 1975: 352, pl. 10, figs 12–13.

REMARKS

Most of the very small number of specimens from the Bethelsdorp Formation that are referable to this species are damaged. Terquem (1864) illustrated a large number of tests in the original description of *Eoguttulina polygona*, but many of these have been considered to be referable to other species by later authors. For example, Lloyd (1962) considered figures 16, 19, 20, 21, 23a–b, 35 and 39 of Terquem's plate 14 to be characteristic of this species, with the rest referable elsewhere. Bielecka (1975) regarded her Polish material to most closely resemble figures 16 to 20, 21 and 35 of Terquem's plate 14. For the present study the interpretations of

FIGURE 29 (*facing page*)

1. *Eoguttulina liassica* (Strickland). SAM-PQ-MF-2314. BT 1/74, 420–423m. F1296, side view. × 142. **2.** *Eoguttulina* cf. *E. inovroclaviensis* (Bielecka & Pożaryski). SAM-PQ-MF-2309. BT 1/74, Core 2, 467.0m. F1408, side view. × 113. **3–4.** *Eoguttulina* cf. *E. inovroclaviensis* (Bielecka & Pożaryski). **3.** SAM-PQ-MF-2310. BT 1/74, Core 2, 467.3m. F1407, side view. × 120. **4.** SAM-PQ-MF-2311. BT 1/74, Core 2, 467.0m. F1406, side view. × 113. **5.** *Eoguttulina* cf. *E. metensis* (Terquem). SAM-PQ-MF-2315. SW 1/08, 2100'. F1410, side view. × 116. **6.** *Eoguttulina oolithica* (Terquem). SAM-PQ-MF-2316. BT 1/74, Core 2, 467.0m. F1409, side view. × 128. **7–8.** *Eoguttulina polygona* (Terquem). **7.** SAM-PQ-MF-2317. ST 1/71, 1280–1285m. F1404, side view. × 104. **8.** SAM-PQ-MF-2351. BT 1/74, 357–360m. F1405, side view. × 136. **9–10.** *Globulina prisca* (Reuss). **9.** SAM-PQ-MF-2318. ST 1/71, 1175–1180m. F1299, side view. × 150. **10.** SAM-PQ-MF-2319. ST 1/71, 1175–1180m. F1300, side view. × 160. **11.** *Pyrulina* sp. SAM-PQ-MF-2320. BT 1/74, Core 2, 467.30m. F1330, side view. × 137. **12.** *Bullopore laevis* (Sollas). SAM-PQ-MF-2321. BSP 4798, F1372 view (attached to shell fragment). × 77. **13–14.** *Webbinella subhemisphaerica* Franke. **13.** SAM-PQ-MF-2322. SW 1/08, 2100'. F1309 view (separated from substrate). × 107. **14.** SAM-PQ-MF-2323. SW 1/08, 2100'. F1310 view (separated from substrate). × 102. **15.** *Ramulina fusiformis* Khan. SAM-PQ-MF-2324. BT 1/74, 591–594m. F1327, side view. × 165. **16.** *Fissurina* sp. SAM-PQ-MF-2325. SW 1/08, 2948'. F1359, side view. × 640. **17–18.** *Spirillina tenuissima* Gümbel. **17.** SAM-PQ-MF-2326. SW 1/08, 2948'. F1401 Close-up of perforations. (Same specimen as No. 18). × 1066. **18.** SAM-PQ-MF-2326. SW 1/08, 2948'. F1400, side view. × 300. **19–20.** *Turrispirillina conoidea* (Paalzow). **19.** SAM-PQ-MF-2327. SW 1/08, 2948'. F1402, umbilical view. × 400. **20.** SAM-PQ-MF-2328. SW 1/08, 2948'. F1403, spiral view. × 360.

Lloyd and Bielecka have been followed as closely as possible in the interpretation of *Eoguttulina polygona*. The sutures are weakly depressed, and the last-formed chamber extends for one half, or less, of the test length, in the specimens from the Bethelsdorp Formation.

Eoguttulina polygona was described by Terquem (1864) from the French Lias. Later records indicate this species to range throughout the Jurassic of north-west Europe. Said & Barakat (1958) obtained specimens referred to this species from the Bajocian, Callovian and Kimmeridgian succession of Gebel Maghara, Sinai, Egypt. Lloyd (1962) noted the species to occur in the type Kimmeridgian of Dorset, England, while Bielecka (1975) found it to be present in the Portlandian of Poland. Espitalié & Sigal (1963b: pl. 30, fig. 16) record a similar form in the Bathonian-Callovian of the Mahajanga Basin, Madagascar, but the Bethelsdorp Formation tests are less slender, more stocky than the Madagascar test.

OCCURRENCE IN THE BETHELSDORP FORMATION

294–297m, 357–360m, 420–423m, 467.0 to 467.30m in BT 1/74; 1270 to 1285m in ST 1/71; not in SW 1/08 or BSP.

Genus GLOBULINA d'Orbigny, in de la Sagra, 1839

Globulina prisca (Reuss, 1863)

Fig. 29, nos 9–10.

Polymorphina (*Globulina*) *prisca* Reuss, 1863: 79, pl. 9, fig. 8.

Globulina prisca (Reuss); Szejn, 1957: 75, 244, pl. 9, figs 83a–b; McLachlan *et al.*, 1976b: 333, fig. 17, no. 2; McLachlan *et al.*, 1976a: 358, fig. 13, nos 6–7.

REMARKS

The specimens from the Portlandian Bethelsdorp Formation compare well with the original description and illustration of this species, although many tests are rather more pear-shaped than ovate in outline. Tests referred to this species from the Bethelsdorp Formation are usually subtly pyriform, whereas those from the Sundays River Formation are always elongate-ovate in outline. Because of variable preservation of these tests, the chamber arrangement is not always clear, and some poorly preserved tests referred here may prove to be juveniles of *Eoguttulina* species. *Globulina prisca* has previously been described from Early Cretaceous rocks in South Africa by McLachlan *et al.* (1976a, 1976b) and by McMillan (2003a). *Globulina prisca* has been widely recorded throughout the world in deposits of Cretaceous age: a characteristic which tends towards the probability that this species is a plexus of exceptionally poorly ornamented, conservative individuals that cannot be effectively speciated.

OCCURRENCE IN THE BETHELSDORP FORMATION

11477 in BSP; 1170 to 1415m in ST 1/71; 2100, 2140 and 2948' in SW 1/08; 366 to 467.30m, and 591–594m in BT 1/74.

Genus PYRULINA d'Orbigny, 1839

Pyrulina sp.

Fig. 29, no. 11.

REMARKS

One test with an unusually small initial part; test widening to maximum width at mid-height, at level of final pair of chambers. This test is distinctly unlike the tests of *Pyrulina cylindroides* (Roemer) reported by McLachlan *et al.* (1976b: 333, fig. 17, no. 4) at Mngazana. The main difference is in the rapidly flaring character of the Bethelsdorp Formation test.

OCCURRENCE IN THE BETHELSDORP FORMATION

Single test, at 467.30m in BT 1/74 only.

Subfamily WEBBINELLINAE Rhumbler, 1904

Genus BULLOPORA Quenstedt, 1856

Bullopورا laevis (Sollas, 1877)

Fig. 29, no. 12.

Webbina laevis Sollas, 1877: 103, pl. 6, figs 1–3.

Vitriwebbina laevis (Sollas); Chapman, 1896: 585, pl. 12, fig. 12.

Bullopورا laevis (Sollas); Tappan, 1940: 115, pl. 18, fig. 6; McMillan, 2003a: 221, figs 65K–L, 66A–B.

REMARKS

Comments on this species have previously been given by McMillan (2003a). The tests obtained from the Bethelsdorp Formation are virtually identical in their test morphology to those of the Sundays River Formation, and to those illustrated by Sollas (1877). The virtual absence of stoloniferous necks in all studied specimens clearly distinguishes them from tests of the Jurassic species *Bullopورا rostrata* Quenstedt, which are marked by unusually elongate necks.

Sollas (1877) described *Bullopورا laevis* from the Cambridge Greensand of England (Cenomanian), and most later records are from Albion or Cenomanian rocks.

OCCURRENCE IN THE BETHELSDORP FORMATION

4798, 4901, possibly also 4904 in BSP; 420–423m in BT 1/74; not in ST 1/71 or SW 1/08.

Genus WEBBINELLA Rhumbler, 1904

Webbinella subhemisphaerica Franke, 1936

Fig. 29, nos 13–14.

Webbinella subhemisphaerica Franke, 1936: 11, pl. 1, fig. 4; McLachlan *et al.*, 1976b: 333, fig. 17, no. 5; McLachlan *et al.*, 1976a: 359, fig. 13, no. 10; Kielbowicz *et al.*, 1983: 333, pl. 5, fig. 3; McMillan, 2003a: 220, figs 65I–J.

REMARKS

The comments in McLachlan *et al.* (1976b, p. 333) and McMillan (2003a, p. 220) are also relevant here. One of the specimens of *Webbinella subhemisphaerica* from the Bethelsdorp Formation displays a small extension to the last-formed spreading chamber, which, although damaged, appears to be an attached juvenile test. *Webbinella subhemisphaerica* was first described from the Lias of northern Germany (Franke, 1936). In South Africa its stratigraphic range is Portlandian to top Hauterivian (McMillan, 2003a). Comparisons and differences between this genus and closely related ones is given by Loeblich & Tappan (1957: 226).

OCCURRENCE IN THE BETHELSDORP FORMATION

Only at 2100' in SW 1/08.

Subfamily RAMULININAE Brady, 1884

Genus RAMULINA T.R. Jones, 1875

Ramulina fusiformis Khan, 1950

Fig. 29, no. 15.

Ramulina fusiformis Khan, 1950: 272, pl. 2, figs 1–2; Seibold & Seibold, 1960: 371, text-fig. 7h; Magniez-Jannin, 1975: 230, pl. 15, figs 21a–b; McMillan, 2003a: 223, fig. 66E.

Ramulina tappanae Bartenstein & Brand, 1951: 322, pl. 11, figs 305–307.

REMARKS

This species is characterised by elongate-ovate chambers with a finely hispid surface ornamentation. The chambers are only very rarely found joined to each other. Magniez-Jannin (1975) has shown this species to exhibit considerable variation, particularly in the degree of chamber inflation, with some chambers becoming almost

globular; in the size of the interconnecting stoloniferous necks, some being very narrow and others wide; and in the height of the hispid surface ornamentation.

Tests from the Bethelsdorp Formation compare closely with specimens illustrated by Khan (1950) and Bartenstein & Brand (1951), in particular. Tests from the Portlandian Bethelsdorp Formation and the Late Valanginian to Hauterivian Sundays River Formation appear to be essentially identical. Khan (1950) obtained his specimens from the Gault Clay (Albian) of southern England, and most subsequent records are from the Albian.

OCCURRENCE IN THE BETHELSDORP FORMATION

591–594m only in BT 1/74; 4798 and 11477 in BSP; 2948' in SW 1/08; absent in ST 1/71.

Family ELLIPSOLAGENIDAE A. Silvestri, 1923

Subfamily ELLIPSOLAGENINAE A. Silvestri, 1923

Genus FISSURINA Reuss, 1850

Fissurina sp.

Fig. 29, no. 16.

REMARKS

Although more common in rocks of Cainozoic age, there are sporadic records through the Cretaceous, but almost none in the Jurassic succession: most early records are of unornamented tests. Loeblich & Tappan (1988) consider its stratigraphic range as “Cretaceous to Holocene”, without indicating from which level in the Cretaceous it appears. The single specimen of *Fissurina* from the Bethelsdorp Formation consequently must be a very early representative of the genus.

This singular specimen is subcircular in outline, with maximum width at approximately mid-height. The test is slightly compressed. The test periphery is subrounded in cross-section, with no indication of a peripheral keel. The surface of the test is ornamented with low, irregular, randomly-orientated, almost worm-like ridges, with intervening shallow depressions. This ornamentation becomes less intense around the aperture. The aperture is a long thin slit, terminally sited, and oriented in the plane of compression of the test. At the apical point of the test, a very small blunt apical spine is developed. No entosolenian tube could be identified within the chamber cavity, but the form of the test and the character of the aperture are clearly typical of *Fissurina*.

OCCURRENCE IN THE BETHELSDORP FORMATION

Only in 2948', SW 1/08.

Family SPIRILLINIDAE Reuss & Fritsch, 1861

Genus SPIRILLINA Ehrenberg, 1843

Spirillina tenuissima Gümbel, 1862

Fig. 29, nos 17–18.

Spirillina tenuissima Gümbel, 1862: 214, pl. 4, figs 12a–b; Barnard, 1953: 192; Bielecka, 1960a: 87, 145, pl. 8, figs 68–69; Espitalié & Sigal, 1963b: 65, pl. 30, figs 19–20; Hanzlíková, 1965: 93, pl. 9, figs 19, 23a–b; Winter, 1970: 42, pl. 4, figs 144a–b; McLachlan *et al.*, 1976b: 334, fig. 17, no. 10; Barnard *et al.*, 1981: 428, pl. 4, figs. 4,8; Gregory, 1989: 188, pl. 1, fig. 23; McMillan, 2003a: 228, figs 67F–G.

REMARKS

Tests referred to *Spirillina tenuissima* occur widely but usually rarely in the marine graben fill successions (Kimmeridgian to Hauterivian) preserved around the South African continental margin (see McMillan, 2003a, p. 228). The few tests from the Portlandian Bethelsdorp Formation are closely similar to the test illustrated and described by Gümbel (1862), as well as those detailed from the Mngazana Formation (McLachlan *et al.*, 1976b), except that their coiling arrangement is rather more irregular. It is not known whether this is a reflection of the much shallower marine, and possibly more stressful environment that the Bethelsdorp Formation individuals occupied, in contrast to the often distinctly deep-water milieux they occupied in the proximal Mngazana Basin (McLachlan *et al.*, 1976b) and the distal Algoa and Gamtoos Basins (McMillan, 2003a).

Spirillina tenuissima was first described from the Oxfordian succession of Streiberg, Bavaria, Germany by Gümbel (1862). Later authors have described it from the Callovian to Oxfordian of Poland (Bielecka, 1960a, 1960b, 1960c), from the Oxfordian of Redcliff Point near Weymouth, England (Barnard, 1953), from the Late Oxfordian to Kimmeridgian Klentnice beds of the Czech Republic (Hanzlíková, 1965), from the Kimmeridgian of south-east Germany (Winter, 1970), the Callovian-Oxfordian of England (Barnard *et al.*, 1981), and the Kimmeridgian of north-east Scotland (Gregory, 1989). In southern Africa, Espitalié & Sigal (1963b) identified it in Cenozones C and D (Kimmeridgian to Early Valanginian) of the Mahajanga Basin, north-west Madagascar, McLachlan *et al.* (1976b) reported it in the later Valanginian of the Mngazana Basin, while McMillan (2003a) noted it in the Late Hauterivian of the Algoa Basin and the Late Valanginian of the offshore Gamtoos Basin.

OCCURRENCE IN THE BETHELSDORP FORMATION

Only in sample 2948', SW 1/08.

Genus TURRISPIRILLINA Cushman, 1927

Turrispirillina conoidea (Paalzow, 1917)

Fig. 29, nos 19–20.

Spirillina conoidea Paalzow, 1917: 217, pl. 41, figs 8a–b; Bartenstein & Brand, 1937: 132.*Turrispirillina conoidea* (Paalzow); Loeblich & Tappan, 1988: 305, pl. 319, figs 8–10.

REMARKS

Several specimens of *Turrispirillina* from the Bethelsdorp Formation appear compatible with Paalzow's description and illustrations of *Turrispirillina conoidea*. The southern African specimens possess distinct shell thickenings over the initial part on both the spiral and umbilical sides of the test, so that the early coiling is not very clear. There is a complete absence of nodes or similar markings on the thickening on the umbilical surface, which would otherwise suggest the placing of these specimens in the genus *Trocholina*.

The illustrations of *Turrispirillina conoidea* given by Paalzow (1917) show the initial part of the test to form a cone, when viewed from the side. In contrast, the southern African tests display a rather more rounded initial part. In addition, the test perforations on the umbilical side of the last-formed whorl are mostly not clearly apparent in the Bethelsdorp Formation tests. Paalzow (1917) initially described *Turrispirillina conoidea* from the Schwammgerel (Oxfordian) of Würgau in Oberfranken, southern Germany. Bartenstein & Brand (1937) obtained their material from the Lias δ and ζ (Pliensbachian to Toarcian) of north-west Germany.

OCCURRENCE IN THE BETHELSDORP FORMATION

Only in sample 2948', SW 1/08.

Family PATELLINIDAE Rhumbler, 1906

Subfamily PATELLININAE Rhumbler, 1906

Genus PATELLINA Williamson, 1858

Patellina oolithica Terquem, 1883

Fig. 30, no. 1.

Patellina oolithica Terquem, 1883: 382, pl. 45, figs 3a–c, 4; Bartenstein & Brand, 1937: 132; Cifelli, 1959: 335, pl. 7, figs 21–22.

REMARKS

Several species of *Patellina* have been described from the European and North American Jurassic successions, but the limits of these species frequently appear

unclear. Differences in height of test, thickness of test wall, rate of increase in size of chambers, and so on, can be considered variations well within that acceptable for a species which adapts these features of its test in response to environmental conditions. This is especially pertinent for the genus *Patellina*, extant tests of which attach to a robust substrate by means of its pseudopodia: morphological differences in each test can be considered as responses to water conditions prevalent around each individual. In consequence of these considerations, it is likely that, for example, *Patellina douvillei*, described by Said & Barakat (1958) from the Bathonian succession at Gebel Maghara, Sinai, Egypt, and *Patellina crista*, described by Lalicker (1950) from the Ellis Group (Bathonian to Oxfordian) of Montana, USA, should both be considered synonymous with *Patellina oolithica*. Further amalgamation of Jurassic *Patellina* species is probably necessary.

Terquem (1883) first described *Patellina oolithica* from the Bajocian to Bathonian *parkinsoni* zone of Fontoy, Moselle, France. Cifelli (1959) obtained examples from various localities of the English Bathonian.

OCCURRENCE IN THE BETHELSDORP FORMATION

Only in sample 2948', SW 1/08.

Family CERATOBULIMINIDAE Cushman, 1927
Subfamily REINHOLDELLINAE Seiglie & Bermúdez, 1965
Genus REINHOLDELLA Brotzen, 1948

Reinholdella costifera (Terquem, 1883)

Fig. 30, nos 2–5.

Epistomina costifera Terquem, 1883: 377, pl. 43, figs 3–6; Bartenstein & Brand, 1937: 191, pl. 11B, figs 30a–c; pl. 11C, figs 1a–c.

Reinholdella costifera (Terquem); Ohm, 1967: 111, pl. 16, fig. 12, text-fig. 7.

REMARKS

Pazdro (1969, p. 30) noted that none of the illustrations, nor the description given by Terquem (1883) for this species provide much indication of its true generic position. In addition it appears that a number of different forms were included by Terquem under this name. Pazdro (op. cit.) re-examined the locality near Warsaw that was sampled by Terquem, but she found only specimens of *Epistomina*, possibly suggesting that Terquem's species is a true *Epistomina* species. Williamson & Stam (1988) regarded the species to be an *Epistomina*. Because of these taxonomic problems, the concept of *Reinholdella costifera* as presented by Ohm (1967) is provisionally followed here. Consequently, it is possible that the distinctive *Reinholdella* specimens referred to Terquem's species may warrant a new name.

The specimens from the onshore Uitenhage Trough compare closely with the illustrations and description of *Reinholdella costifera* given by Ohm (1967). The size of the umbilical plug is slightly larger, and there are five or six chambers in the final whorl of the South African tests rather than five to seven (Ohm). Both in the tests figured by Ohm and in the examples from the Uitenhage Trough, the sutures on the spiral side of the test are slightly raised.

Terquem (1883) originally described this species from the *parkinsoni* Zone (Bajocian–Bathonian) of Fontoy, Moselle, France: additional material was from near Warsaw, Poland. Ohm (1967) considered its full stratigraphic range as *parkinsoni* Zone (Bajocian–Bathonian) to *coronatum* Zone (Callovian).

OCCURRENCE IN THE BETHELSDORP FORMATION

Only in sample 2948', SW 1/08.

Family EPISTOMINIDAE Wedekind, 1937

Subfamily EPISTOMININAE Wedekind, 1937

Genus EPISTOMINA Terquem, 1883

Epistomina parastelligera (Hofker, 1954)

Fig. 30, nos 6–13.

Brotzenia parastelligera Hofker, 1954: 180, text-figs 4–6; Lloyd, 1962: 377, pl. 2, figs 8a–c, text-fig. 7B; Hanzlíková, 1965: 95, pl. 8, figs 5–8.

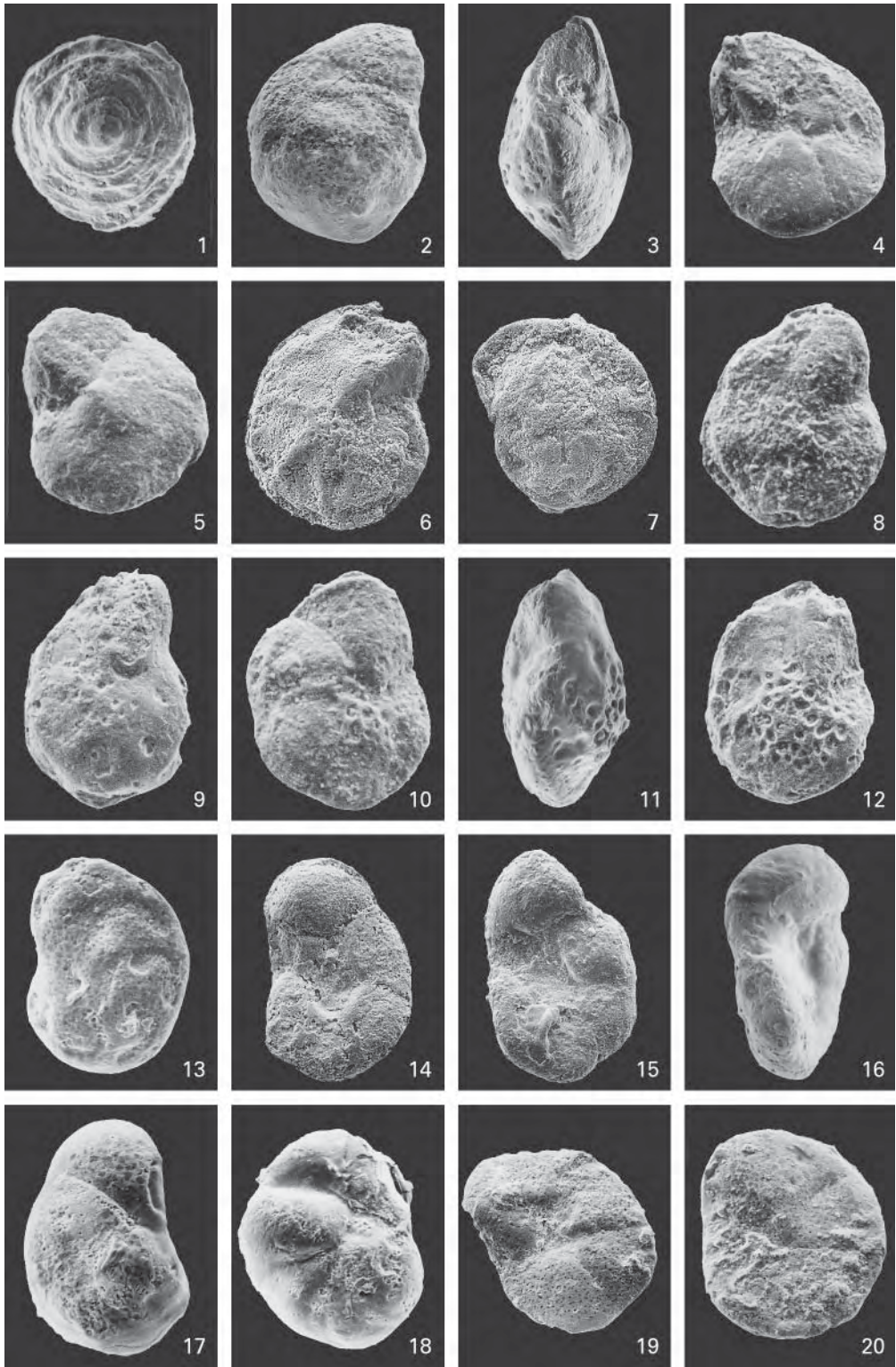
Epistomina parastelligera (Hofker); Lutze, 1960: 491, pl. 33, figs 3a–c, 6a–c; Cordey, 1962: 395, pl. 48, figs 41a–c, 42; Wernli, 1971: 345, pl. 3, figs 13–14, 16–17.

Epistomina uhligi Mjatluk; Williamson & Stam, 1988: 146, pl. 1, figs 6–7.

see *Epistomina regularis* Terquem; Morris & Coleman, 1989: 224, pl. 6.3.7, fig. 12 only.

REMARKS

This species has been encountered widely by most authors engaged with researching Middle and Late Jurassic foraminifera, although considerable variation exists in the interpretation of the species. Bethelsdorp Formation specimens display variation in the nature of the test periphery and outline, and the surface ornamentation. The form of the test periphery in some specimens is almost bicarinate, with a poorly developed sub-angular keel both on the spiral and on the umbilical sides of the closed peripheral apertures. Most South African specimens possess a lower, less conical umbilical side than the tests illustrated by Hofker (1954). In addition, a few specimens from the Bethelsdorp Formation display a small, rather variable area of fine surface reticulation around the umbilicus on both the spiral and umbilical sides of the test. The reticulation amounts to about five small depressions, but in one example, reticulations are more numerous and cover much more of the



test surface. Illustrations of *Epistomina parastelligera* given by Lloyd (1962) and Hanzlíková (1965) include specimens with strongly raised sutures, but such tests have not been found in the onshore Uitenhage Trough. In contrast, the tests illustrated by Williamson & Stam (1988) of *Epistomina uhligi* Mjatliuk, regarded by them as a senior synonym of *Epistomina parastelligera*, are of an entirely smooth test, without reticulations or septal ridges. Some tests of *Epistomina regularis* Terquem display a comparable umbonal reticulation (Morris & Coleman, 1989: 224, pl. 6.3.7, fig. 12 only). Nonetheless, the test morphology of specimens here allocated to *Epistomina parastelligera* is entirely unlike that of any of the *Epistomina* species in the Sundays River Formation (McMillan, 2003a). Taxonomic confusions notably occur between *Epistomina parastelligera* and *Epistomina stelligera*, and some resolving of taxonomy is necessary (Pazdro, 1969, p. 27).

The reticulated specimens mentioned above have been included within *Epistomina parastelligera*, as the ornamented and unornamented forms are otherwise much the same. However, alternatively the reticulated tests may prove to be referable to *Epistomina stellicostata* (Bielecka & Pożaryski, 1954, p. 71, 200, pl. 12, figs 60a–c), described from the Kimmeridgian-Portlandian succession of central Poland. They

FIGURE 30 (facing page)

1. *Patellina oolithica* Terquem. SAM-PQ-MF-2329. SW 1/08, 2948'. F1399, spiral view. $\times 280$. **2–5.** *Reinholdella costifera* (Terquem). **2.** SAM-PQ-MF-2330. SW 1/08, 2948'. F1380, spiral view (same specimen as No. 4). $\times 386$. **3.** SAM-PQ-MF-2331. SW 1/08, 2948'. F1379, side view (same specimen as No. 5). $\times 340$. **4.** SAM-PQ-MF-2330. SW 1/08, 2948'. F1307, umbilical view (same specimen as No. 2). $\times 300$. **5.** SAM-PQ-MF-2331. SW 1/08, 2948'. F1308, umbilical view (same specimen as No. 3). $\times 300$. **6–13.** *Epistomina parastelligera* (Hofker). **6.** SAM-PQ-MF-2332. BSP 11477, F1346, umbilical view. $\times 300$. **7.** SAM-PQ-MF-2333. Bethelsdorp Salt Pan 11477, F1348, spiral view. $\times 240$. **8.** SAM-PQ-MF-2334. SW 1/08, 2100'. F1304, umbilical view (few umbilical reticulations). $\times 256$. **9.** SAM-PQ-MF-2335. BT 1/74, 591–594m. F1302, umbilical view (few umbilical reticulations). $\times 256$. **10.** SAM-PQ-MF-2336. SW 1/08, 2100'. F1305, umbilical view (few umbilical reticulations). $\times 330$. **11.** SAM-PQ-MF-2337. BT 1/74, 591–594m. F1396, side view (moderate umbilical reticulations; same specimen as No. 12). $\times 320$. **12.** SAM-PQ-MF-2337. BT 1/74, 591–594m. F1303, umbilical view. $\times 248$. **13.** SAM-PQ-MF-2338. BT 1/74, 591–594m. F1398, spiral view (with L and C-shaped “glyphs”). $\times 300$. **14–18.** *Conorboides mariscus* n.sp. McMillan. **14.** Paratype. SAM-PQ-MF-2339. BT 1/74, Core 2, 467.0m. F1338, umbilical view. $\times 256$. **15.** Holotype. SAM-PQ-MF-2340. BT 1/74, Core 2, 467.0m. F1337, umbilical view. $\times 220$. **16.** Holotype. SAM-PQ-MF-2340. BT 1/74, Core 2, 467.0m. F1393, side view (same specimen as No. 15). $\times 213$. **17.** Paratype. SAM-PQ-MF-2339. BT 1/74, Core 2, 467.0m. F1394, spiral view (same specimen as No. 14). $\times 220$. **18.** Paratype. SAM-PQ-MF-2342. BT 1/74, Core 2, 467.0m. F1392, spiral view. $\times 248$. **19–20.** *Conorboides nudus* (Terquem). **19.** SAM-PQ-MF-2343. SW 1/08, 2948'. F1389, umbilical view. $\times 386$. **20.** SAM-PQ-MF-2344. SW 1/08, 2948'. F1390, umbilical view. $\times 413$.

also are close to a morphologically similar species, *Epistomina minutereticulata* (Espitalié & Sigal, 1963b), described from the mid-Callovian to Early Oxfordian succession (Cenozoone B) of the Mahajanga Basin, Madagascar. However too few reticulated tests have been found up to now in the Portlandian Bethelsdorp Formation to warrant a confident placing in either of these species.

Hofker (1954) originally described *Epistomina parastelligera* from the Middle Jurassic succession, but noted that it occurred in rocks as young as Hauterivian. The large majority of later records are from the Jurassic: Domerian Lias of southern Germany (Welzel, 1968); Callovian-Oxfordian of north-west Germany (Lutze, 1960); Callovian-Oxfordian of Poland (Bielecka, 1960a); Bathonian-Callovian of Poland (Pazdro, 1969); Late Oxfordian-Kimmeridgian of the Czech Republic (Hanzlíková, 1965); Early Oxfordian of the Isle of Skye, Scotland (Cordey, 1962); type Kimmeridgian of Dorset, England (Lloyd, 1962); Callovian of Brora, Scotland (Gordon, 1967); Callovian to mid-Oxfordian of the Jura Méridional, France (Wernli, 1971); Bajocian-Late Oxfordian of Israel (Maync, 1966); and the Callovian-Kimmeridgian of Sinai, Egypt (Said & Barakat, 1958).

OCCURRENCE IN THE BETHELSDORP FORMATION

420–423m, 467.0 to 467.3m, 591 to 612m in BT 1/74; 2100', 2948', 3023' in SW 1/08; 11477 in BSP; absent in ST 1/71.

Family CONORBOIDIDAE Thalmann, 1952

Genus CONORBOIDES Hofker, 1952

Conorboides mariscus n. sp. McMillan

Fig. 30, nos 14–18.

DESCRIPTION

Test small, chambers arranged in a low trochospiral coil, with spiral side of test convex and umbilical side concave. Axial periphery broadly rounded to subrounded, and equatorial periphery lobulate. Chambers increase steadily in size as added, and are arranged in 1 to 1½ whorls, with six or seven chambers in the last-formed whorl. Last few chambers are strongly inflated, especially on the spiral side of the test. Sutures on spiral side strongly oblique, curved, limbate, initially lightly raised, but between the final few chambers becoming strongly depressed. Sutures on umbilical side indistinct, radiate, straight to slightly curved, initially flush, later becoming lightly depressed. Proloculus spherical, distinctly protruding above the surface of the later chambers on the spiral side. Umbilicus deep and broad, and encircled by distinct narrow apertural flaps developed at the umbilical margin on the chambers of the last-formed whorl, suggesting that all these chambers open directly into the umbilicus beneath the flaps. Aperture a low arched opening on

the last-formed chamber, interiomarginal and umbilical in position. Any structures developed within chamber cavity, if there are any, not apparent from exterior view. Most specimens dextrally coiled.

VARIATION

The degree of inflation of the final few chambers is very variable, especially on the spiral side of the test. In consequence, the final chamber, in particular, can vary considerably in shape.

DERIVATIO NOMINIS

Named from *mariscus*, *-a*, *-um* (L.), indicating marshy, the interpreted environment of much of the Bethelsdorp Formation succession in the onshore Uitenhage Trough.

NUMBER OF SPECIMENS STUDIED

Twelve.

HOLOTYPE

Fig. 30, nos 15–16, core sample 467.0m, core 2, borehole BT 1/74.

STRATUS TYPICUS

Borehole BT 1/74, core 2, 467.0m depth, Portlandian Bethelsdorp Formation, onshore Uitenhage Trough, Algoa Basin.

PARATYPES

Four specimens from core sample 467.0m, core 2, BT 1/74, two illustrated as Fig. 30, nos 14, 17–18.

REMARKS

Conorboides species of similar type to *Conorboides mariscus* are known widely in the later Jurassic succession of north-west Europe. The most closely comparable species seems to be *Conorboides pygmaea*, described by Cordey (1962) from the Oxfordian succession of the Isle of Skye, Scotland. However, Cordey's species does not feature a strongly depressed umbilicus, nor strongly inflated later chambers, nor apertural lips surrounding the umbilicus, nor curved, limbate sutures on the spiral side, all of which are features of *Conorboides mariscus*.

Lloyd (1962) described *Conorboides marginata* from the type Kimmeridgian sections of the Dorset coast, England, but this species differs from *Conorboides mariscus* in possessing subglobular chambers throughout, and also a sub-marginal, low rib on the umbilical side. *Conorboides paulus*, described by Pazdro (1969) from the Bathonian of Poland, is distinguished from *Conorboides mariscus* in the possession of a sharply angled test periphery, and only four or five chambers in the final whorl.

OCCURRENCE IN THE BETHELSDORP FORMATION

467.0m, 467.30m, 591–594m in BT 1/74; 2100', 2948', 3023' in SW 1/08; absent in BSP and ST 1/71.

Conorboides nudus (Terquem, 1883)

Fig. 30, nos 19–20. Fig. 31, no. 1.

Epistomina nuda Terquem, 1883: 376, pl. 43, figs 2a–b (*non* figs 1a–c).

Conorboides nuda (Terquem); Lutze, 1960: 492, pl. 33, figs 8a–c; Gordon, 1967: 458, pl. 4, fig. 30.

REMARKS

The few tests obtained from the Bethelsdorp Formation compare most closely with the specimen illustrated by Gordon (1967), particularly in the presence, in some specimens, of a small, shallow umbilical depression on the umbilical side of the test. The sutures on the spiral side are faintly raised, and there are five or six chambers in the last-formed whorl. Some of the South African shells show the *Reinholdella*-like indentation of the last-formed inter-cameral suture-line, which is also well illustrated by Lutze (1960).

First described (Terquem, 1883) from the Bajocian-Bathonian *Parkinsoni*-zone of Fontoy, Moselle, France; also present in the mid-Callovian succession of north-west Germany (Lutze, 1960); and in the Callovian Brora Argillaceous Series of Brora, Scotland (Gordon, 1967). Williamson & Stam (1988) regarded this species to be referable to the genus *Epistomina*.

OCCURRENCE IN THE BETHELSDORP FORMATION

Only in sample 2948', SW 1/08.

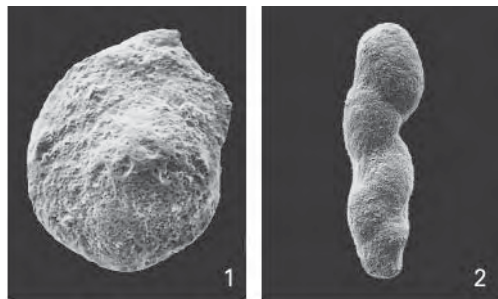


FIGURE 31

1. *Conorboides nudus* (Terquem). SAM-PQ-MF-2345. SW 1/08, 2948'. F1391, spiral view. $\times 400$. 2. ?*Ellipsoidella* sp. SAM-PQ-MF-2346. ST 1/71, 1440–1445m. F1335, side view. (Cast of foraminifera test). $\times 106$.

FAMILY PLEUROSATOMELLIDAE

Genus ELLIPSOIDEA Heron-Allen & Earland, 1910

? *Ellipsoidella* sp.

Fig. 31, no. 2.

see *Ellipsoidella pleurostomelloides* Heron-Allen & Earland, 1910: 410; Loeblich & Tappan, 1964: 728, fig. 594, nos 6–7.

REMARKS

One test was found in Peak 8, where marine influence is strongest, in borehole ST 1/71. This is an infilling of the test, the shell itself having disappeared through calcite dissolution, but the chamber arrangement, initially biserial and becoming uniserial and cuneate, is clearly evident. The specimen is similar to tests of *Ellipsoidella pleurostomelloides*, described from the Turonian Chalk of Southern England, a genus not at all typical of the Late Jurassic or Early Cretaceous successions of Southern England or elsewhere. The major distinction between *E. pleurostomelloides* (see Loeblich & Tappan, 1964, 1988) and the Bethelsdorp Formation test is that the English tests are compressed perpendicular to the equatorial plane, whereas the South African test is compressed parallel to the equatorial plane. The aperture is not very clearly preserved, but appears to be an elongate slit almost terminal in position on the last-formed chamber, and oriented in the plane of compression of the test. The hooded apertural structures of true *Ellipsoidella* and some other pleurostomellids are not seen on this single cast.

OCCURRENCE IN THE BETHELSDORP FORMATION

Only 1440–1445m, ST 1/71.

OTHER MICROFOSSIL GROUPS AND MACROFOSSIL ELEMENTS

A great variety of faunal and floral skeletal elements were obtained from the Bethelsdorp Formation during the course of the foraminiferal study. This wide diversity reflects the generally well-oxygenated, hyposaline estuarine channels, hypersaline mudflats and normal marine innermost neritic environments of deposition evident in the Bethelsdorp Formation. The following list excludes charophyte oogonia and marine and non-marine ostracods, which, it is hoped, will be described elsewhere. Distinctive forms of charophyte oogonia and non-marine ostracods occur in the Colchester Formation, while charophyte oogonia, non-marine and marine ostracods occur throughout the Bethelsdorp Formation, sometimes together, sometimes separately. Not surprisingly, given the mostly shallow environment of deposition, no radiolaria or planktic foraminifera were found in any of the studied samples.

1. BRYOZOANS

A variety of bryozoan morphotypes have been encountered in the Bethelsdorp Formation. Both attached, encrusting forms, as well as free-growing forms occur. The encrusting forms are especially noticeable on bivalve and oyster shell fragments from shelly bands exposed in the Bethelsdorp Salt Pan outcrops.

2. POSSIBLE CORALS

Two questionable solitary corals were obtained from samples 4901 and 4904 from the Bethelsdorp Salt Pan exposures. It is uncertain whether they are true corals or a distinctive type of bryozoan.

3. CALCAREOUS ALGA SEGMENTS

At several horizons in the Bethelsdorp Formation succession in borehole BT 1/74 probable calcareous alga segments occur. These are similar to those known from the extant genus *Corallina*.

4. CALCAREOUS WORM TUBES

Generally from the more marine horizons in both the boreholes and outcrops occur various types of calcareous worm tubes. Some are individual and solitary, while others are closely packed and colonial. All consist of calcareous tubes, usually

open at both ends, and displaying growth lines on the exterior. In addition, in the shelly horizons exposed in the Bethelsdorp Salt Pan outcrops, serpulid worm tubes were found cemented to mollusc shell fragments.

5. SCAPHOPODS

A few scaphopod tubes were identified in the Bethelsdorp Salt Pan samples. All examples possess the characteristic curve to the tube, with a slight taper from one end to the other. Some are smooth and unornamented, while others are ornamented with longitudinal ribs.

6. CRUSTACEAN CLAWS AND OTHER SKELETAL FRAGMENTS

A small number of crustacean claw elements, as well as limb and body shell fragments were found widely through the Bethelsdorp Formation. They were found to be particularly common in core 2 of borehole BT 1/74. It is not possible to determine which group of crustaceans constructed these elements.

7. GASTROPODS

Of all the macrofossil groups encountered in the course of this study, gastropods proved to be by far the most abundant. There appear to be two or three essentially thin and smooth-walled, chitinous gastropod species in the lacustrine sediments of the Colchester Formation. However, at some horizons in the mudflat sediments of the Bethelsdorp Formation in the BT 1/74 section, thousands of small-sized specimens were encountered. Destruction of the larger shells by the action of the drilling bit in the course of rotary drilling has probably reduced the numbers present. The gastropods from the Bethelsdorp Salt Pan are generally thick-walled forms ornamented with thick ribs and nodes. Many of the thinner-shelled forms have experienced flattening or partial crushing of the shell.

8. BIVALVES

In general, bivalves were found to be much less common than gastropods. As well as for natural reasons, this may be partly due to destruction of larger shells during drilling, and also partly due to fracturing and disintegration of the valves by compression and compaction of overlying sediment. Most bivalves were recovered as indeterminate shell fragments, after micropalaeontological washing and processing of samples had removed the supporting sediment. Comparatively few fragments could be confidently regarded as originating from bivalve shells, for example, those displaying hinge-line structures. There are a small number of thin-walled bivalve shells, of one or two species, present in the Colchester Formation, but quite a variety of thick-walled forms occur in the Bethelsdorp Formation.

Two particular groups of bivalves were recognised in the Bethelsdorp Formation of the onshore Uitenhage Trough as having special significance: the *Inoceramus* and *Ostrea* groups. *Inoceramus* occurs solely as fragmented small blocks of prisms, or as

individual disarticulated prisms, in many of the studied samples from Bethelsdorp Salt Pan, as well as in the lower half of the Bethelsdorp Formation in the three deep borehole sections. The presence of *Inoceramus* prisms in the onshore Uitenhage Trough depositional milieu has been taken to indicate normal marine, inner neritic environments of deposition.

Ostrea (oysters) shells occur at several horizons in the BT 1/74 and ST 1/71 sections, and in the Bethelsdorp Salt Pan outcrops of the Bethelsdorp Formation, but they are absent in the Colchester Formation. They are distinguished by their finely lamellar shell structure, and by their distinctive shell and valve shapes. Their localised presence suggests horizons during which innermost neritic, agitated and wave-influenced, slightly hyposaline conditions prevailed. Stow (1871) noted oysters at particular horizons at both Bethelsdorp Salt Pan and North End Lake.

Trigonioid bivalves have been examined in particular detail from the Sundays River Formation and time-equivalent beds, by Pringle (1960) and Cooper (1979a, b, 1991); and Kitchin (1908) examined the complete molluscan assemblage. In contrast, the molluscan assemblages of the Bethelsdorp Formation were last studied by Tate (1867), Stow (1871), Newton (1914) and Haughton (1928), and they would benefit greatly from revision.

9. AMMONITES

Ammonites are widespread in the Sundays River Formation, if not especially common (Cooper, 1981, 1983), but none are yet known from the Bethelsdorp Formation. No microscopic ammonite fragments, or pyritised infillings of protoconch or later chambers, were found during the course of this present foraminifera study.

10. HOLOTHURIAN SCLERITES (FIGURE 32)

A small number of holothurian (sea cucumber) sclerites were identified from samples 11475, 11476 and 11477 at Bethelsdorp Salt Pan, and from the lowest part of the Bethelsdorp Formation section in boreholes BT 1/74 and SW 1/08. All of these sclerites are of the same type. The following taxonomy is based on Frizzell & Exline (1966).



FIGURE 32

Holothurian sclerite. SAM-PQ-MF-2349. $\times 146$.

Family ACHISTRIDAE Frizzell & Exline, 1956

Genus ACHISTRUM Etheridge, 1881

Achistrum sp.

REMARKS

All six specimens from the Bethelsdorp Formation are damaged, none showing the spear preserved. The shank is irregular in cross-section, roughly ovate. Eye oriented at 90° to the plane of greatest diameter of the shank, and presumably also the spear. Eye open, small in diameter, and slightly irregular in shape, centrally placed over shank. The eye is not subdivided, but shows two small peripheral protrusions, at the top and at the base, which extend a way towards each other. These specimens, being damaged, cannot be specifically identified, but they are probably similar to *Achistrum* (*Spinrum*) *bartensteini* Frizzell & Exline. These are the oldest known holothurian sclerites in southern Africa. Very similar forms, broken in the same manner, were found very rarely in the Late Valanginian to Late Hauterivian Sundays River Formation of the Algoa Basin (McMillan, 2003a, p. 257, fig. 78I).

11. CRINOID OSSICLES

From several of the outcrop samples collected at Bethelsdorp Salt Pan, and from the basal part of the Bethelsdorp Formation in all three studied deep boreholes, small to moderate numbers of crinoid (sea-lily) ossicles were found. Most are microscopic oval ossicles, which probably derive from the arms, but a single *Pentacrinus*-type ossicle was obtained from the salt pan outcrops. Similar forms have been illustrated by McLachlan *et al.* (1976a, fig. 16, no. 26) from the Brenton Formation, and by McMillan (2003a, p. 255, fig. 78E–G) from the Sundays River Formation.

12. OPHIUROID OSSICLES

Vertebra-like skeletal elements from the articulated arms of ophiuroids (brittle-stars) occur in varying numbers through much of the Bethelsdorp Formation of the onshore Uitenhage Trough. Variations in ossicle length and diameter, and in degree of complexity occur, suggesting origins from different positions along the arm. Ophiuroid ossicles have previously been illustrated by McLachlan *et al.* (1976a, fig. 16, no. 24) from the Brenton Formation, and by McMillan (2003a, p. 257, fig. 80B) from the Sundays River Formation. The overall skeletal structure of a new ophiuroid species has been described by Shone (1986) from the Sundays River Formation.

13. ECHINOID SPINES AND PLATES

Echinoid (sea-urchin) spines, shell plates and occasional pedicellaria occur rarely in the Bethelsdorp Formation succession in borehole BT 1/74, especially at the base of the formation. However, these elements are common in the samples from

Bethelsdorp Salt Pan, where a wide variety of spine types can be seen, as well as pedicellaria, individual shell plates and larger portions of shell. As early as the mid 19th century, notice was taken of the abundance of sea urchin spines occurring in the outcrops at the salt pan (Atherstone, 1857). Here, flattened spines, spines with triangular cross-section, spines with strong longitudinal ribs, spines with polygonal cross-section and ornamented with thorns very like rose thorns, as well as completely smooth and unornamented spines all occur. In addition, careful washing of some of the studied outcrop samples yielded pieces of echinoid shell with spines and pedicellaria bent over, but still resting next to the boss or attachment points to which they had been attached in life. Such an occurrence clearly indicates that sedimentation of the Bethelsdorp Formation at some periods could be extremely placid.

14. INDETERMINATE ECHINODERM SKELETAL ELEMENTS

Apart from the various echinoderm skeletal debris described above (from holothurians, crinoids, ophiuroids and echinoids), there are also a number of widely occurring elements in the Bethelsdorp Formation which cannot be easily allocated to any particular echinoderm group, but which are obviously echinoderm in origin. Particularly common are semicircular, concavo-convex, elongate and tapering elements with crenulated attachment points at the thicker end. These and other indeterminate skeletal elements may well derive especially from asteroids (starfish).

15. FISH DEBRIS.

Four types of fish debris were identified in the Bethelsdorp Formation: fish bone fragments, fish teeth, fish scales and fish otoliths (ear-bones used by some fish to establish their balance). In contrast, in the lacustrine sediments of the Colchester Formation, only fish bone and fish teeth have been found. In the case of the fish bone fragments in the Bethelsdorp Formation, very few bones are complete, and most are damaged fragments. Fish bone occurs in small to moderate numbers in both the Colchester and the Bethelsdorp Formations.

Small but persistent numbers of fish teeth occur throughout the Bethelsdorp Formation, but occurrences in the Colchester Formation are more sporadic. The greatest diversity of fish teeth forms was identified in borehole BT 1/74, where eight morphotypes were recognised. Only two of these eight were also found to be present in the Colchester Formation.

Morphotype 1: Broad, round and glassy, smooth, with no base.

Morphotype 2: Conical, curved glassy tooth, with ovate cross-section, and distinct, sharp, blade-like margins. Extending from the glassy part is a curved, black, roughened bony stem, circular in cross-section. End of stem is irregularly broken.

Morphotype 3: Small-sized, circular to ovate in cross-section. Small glassy tooth with larger bony stem. Stem is compressed and usually shows a prominent lobe. Where lobe is strongly developed, glassy tooth is more curved.

Morphotype 4: Small conical glassy tooth, with long curved bony stem. Similar to morphotype 2, but lacks a bladed margin, and not ovate in cross-section, but circular.

Morphotype 5: Broad, rounded, glassy, like morphotype 1, but short, with additional bone base.

Morphotype 6: Conical, strongly ribbed, double tooth.

Morphotype 7: Very broad tooth, smooth, dome-shaped, with short opaque bone base.

Morphotype 8: Broadly rounded and strongly ribbed.

Morphotypes 2 and 4 are present in both the Bethelsdorp and the Colchester Formation, the rest only in the Bethelsdorp Formation. It is not yet possible to know if these fish teeth can be correlated with particular fish types known to have been extant in the Late Jurassic period.

A small number of fish scales have been found, most consisting of a diamond-shaped unornamented plate, with an attachment point on an extension developed perpendicularly to the plate. Most examples were from the Bethelsdorp Formation, and only a few from the Colchester Formation. Too few occur for them to be an aid in biostratigraphic correlation.

A small number of fish otoliths (Fig 33, nos 1–2) were found in the Bethelsdorp Formation in the BT 1/74 and ST 1/71 borehole sections, and in the outcrop samples from Bethelsdorp Salt Pan. None have been found in the Colchester Formation. Most of the specimens are sacculiths, and one or two appear to be utriculiths. The

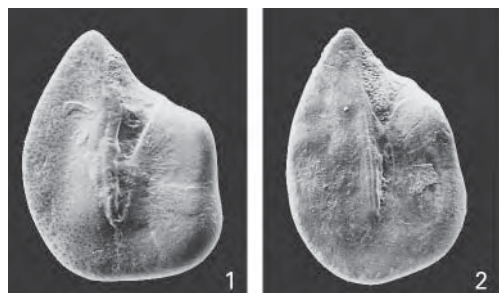


FIGURE 33

1–2. *Fish otolith (sacculith)*. 1. SAM-PQ-MF-2347. BT 1/74, 411–414 m. F1412, internal view. $\times 128$. 2. SAM-PQ-MF-2348. BT 1/74, 411–414 m. F1411, internal view. $\times 106$.

otoliths from the onshore Uitenhage Trough are similar in morphology to those illustrated by Martin & Weiler (1957) from the Aldorf otolith “layer” (Portlandian) of Germany, and from elsewhere in the German Malm succession (Martin & Weiler, 1954). All of the Bethelsdorp Formation otoliths are simple forms, and none possess crenulate margins. They are evidently referable to the leptolepid group of fish (of the genera *Leptolepis* and, or *Leptolepidarum*).

16. FOSSIL WOOD

Fossil wood, plant stems and other plant debris occurs in small quantities through the Bethelsdorp Formation in all of the studied borehole sections, and in almost all of the studied outcrop samples (Chatty and Bethelsdorp Salt Pan). At no horizon is it abundant, and in this respect there is a clear difference between the Bethelsdorp Formation and the proximal Sundays River Formation, which is often full of fossil wood debris.

17. MEGASPORES

Several different types of megaspore were encountered in the borehole and outcrop sections of the Bethelsdorp Formation. Particularly strongly ornamented megaspores were obtained from the lower half of the formation in the BT 1/74 and ST 1/71 borehole sections.

18. MICROCARPOLITHES HEXAGONALIS (“HEXISEDS”)

These distinctive six-sided carbonised structures, without any internal cavity, occur widely in Valanginian and later Cretaceous rocks in South Africa, especially where fluvial sediment input is high. They are widespread in the Sundays River Formation (McMillan, 2003a, p. 259, fig. 80C). They are not present in either the Bethelsdorp Formation or the Colchester Formation. They are known internationally, and are now believed to be the faecal pellets of two particular families of termite (pers. comm., J-P. Colin, France). It appears possible that their first stratigraphic appearance is at or near the Jurassic-Cretaceous boundary.

CONCLUSIONS

The Late Jurassic portion of the Algoa Basin is shown to contain a marine-influenced succession in the proximal (onshore) portion of the Uitenhage Trough. This succession is almost 400m thick, and contains foraminiferal assemblages indicative of inner neritic/marginal marine, hypersaline mudflat and hyposaline estuarine facies. So far as the foraminifera indicate, they are of Portlandian age. This rock unit, here separated from the lacustrine succession of the Colchester Formation and designated the Bethelsdorp Formation, equates with the lower Vaca Muerta Formation of the Neuquén Basin of Andean Argentina. It probably also correlates with part of the Springhill Formation of the Austral Basin in southernmost Argentina. Foraminifera abundances fluctuate substantially through the succession, as do ostracods indicating inner neritic marine environments (*Progonocythere*) and non-marine environments (*Cypridea*). There are eight substantial peaks of foraminifera abundance. Intervening beds are probably non-marine red and green beds. In general environments of the Bethelsdorp Formation shallow gently upwards. Particular foraminifera assemblages reflect specific environments: hypersaline salt marsh and mudflats (monospecific predominance of *Quinqueloculina*); hyposaline channel sediments (*Miliammina* and *Ammomarginulina*); hyposaline inner neritic (*Ammobaculites* and *Haplophragmoides*); normal marine dysoxic (*Eoguttulina*); and normal marine euoxic (diverse inner neritic assemblage of agglutinated and calcareous-walled benthic species).

Red beds is not a signature for the Kirkwood Formation only. It is clear from the detailed bed-by-bed analysis of the outcrop sections around Bethelsdorp Salt Pan and North End Lake by the early geologists Atherstone (1857), Stow (1871) and Haughton (1928), that non-marine red beds comprise a substantial portion of the marine-influenced Bethelsdorp Formation. Fine-grained non-marine and marginal marine beds of the same age also occur in other basins: Heideberg-Riversdale Basin, Oudtshoorn Basin, onshore Gamtoos Basin. These three geologists in particular were some of the earliest sequence stratigraphers in South Africa. Despite insufficient fossil material to establish relative ages for all his stratigraphic sections, Stow's (1871) figures, showing fossil content, or lack of it, bed by bed in the "Saliferous Series", remains a key text. Both the Bethelsdorp and the Colchester Formations represent a specific time-period and environment in the life of the Algoa Basin, and have no connection with the overlying red and green claystones

of the Kirkwood Formation or the underlying Swartkops Formation sandstones. That this is so can be seen by again cross-comparing with the time-equivalent successions and environments of the Neuquén Basin (Tordillo/Quebrada del Sapo Formations; Vaca Muerta Formation; Mulichinco Formation; Agrio Formation), and the Austral Basin (Springhill Formation; Pampa Rincón Formation; Rio Mayer Formation) and Chubut (Katterfeld Formation) of southern South America.

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THE AUTHOR

Ian McMillan was born in 1951 in Kingston-on-Thames, London. Discovered foraminifera in 1972 while at Portsmouth Polytechnic, and completed an M.Sc on Holocene foraminifera of the Agulhas Bank and a Ph.D. on Southern Namibian Late-Quaternary foraminifera. Worked at Soekor (Pty) Ltd as foraminiferal biostratigrapher for most of the period 1972 to 1992, and similarly at De Beers Marine from 1993 to 2003, subsequently working as a contractor. Has advised on about ten theses (at Honours, M.Sc. and Ph.D levels), worked on projects in Sierra Leone, Angola, Namibia, South Africa and Tanzania, and localised projects in Cameroon and Argentina. Looked at the microfossils of about 250 boreholes and 4000 sea floor samples mostly off-shore South Africa. Published a number of articles on South African foraminifera. Likes many styles of music and strange books. Presently lives in Cape Town.

Foraminifera are single-celled Protista, microscopic animals, which occur today in abundance throughout most of the world's oceans. These animals do not fossilise. However they construct tiny shells (tests) composed either of calcium carbonate or by cementing extremely small grains of quartz together. These tests are often very complex constructions, both in terms of how they grow from juvenile to adult, and how they ornament and design the interior and exterior of the test. Foraminifera first appeared in the stratigraphic record during the Cambrian: early forms are simple tubular, coiled tubular or spherical structures. However through time to the present day they have become increasingly sophisticated structures. Foraminifera have been used extensively to date rock successions, and determine past depositional environments, especially for oil and diamond exploration, usually in association with seismic and well log studies. About 220 species of foraminifera are now known from the Late Jurassic and Early Cretaceous Algoa Basin graben fill, and about 30 from the Pliocene to latest Pleistocene covering veneer overlying the onshore basin, and it is probable that further exploration of outcrop sites will lead to the discovery of numerous additional species.

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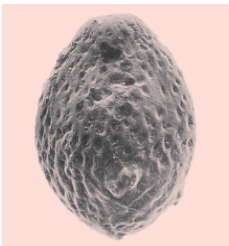
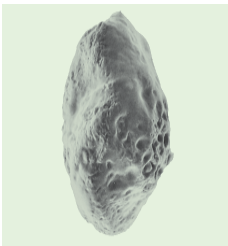


FIGURE 6: STRATIGRAPHIC RANGE CHART FOR BOREHOLE BT/74

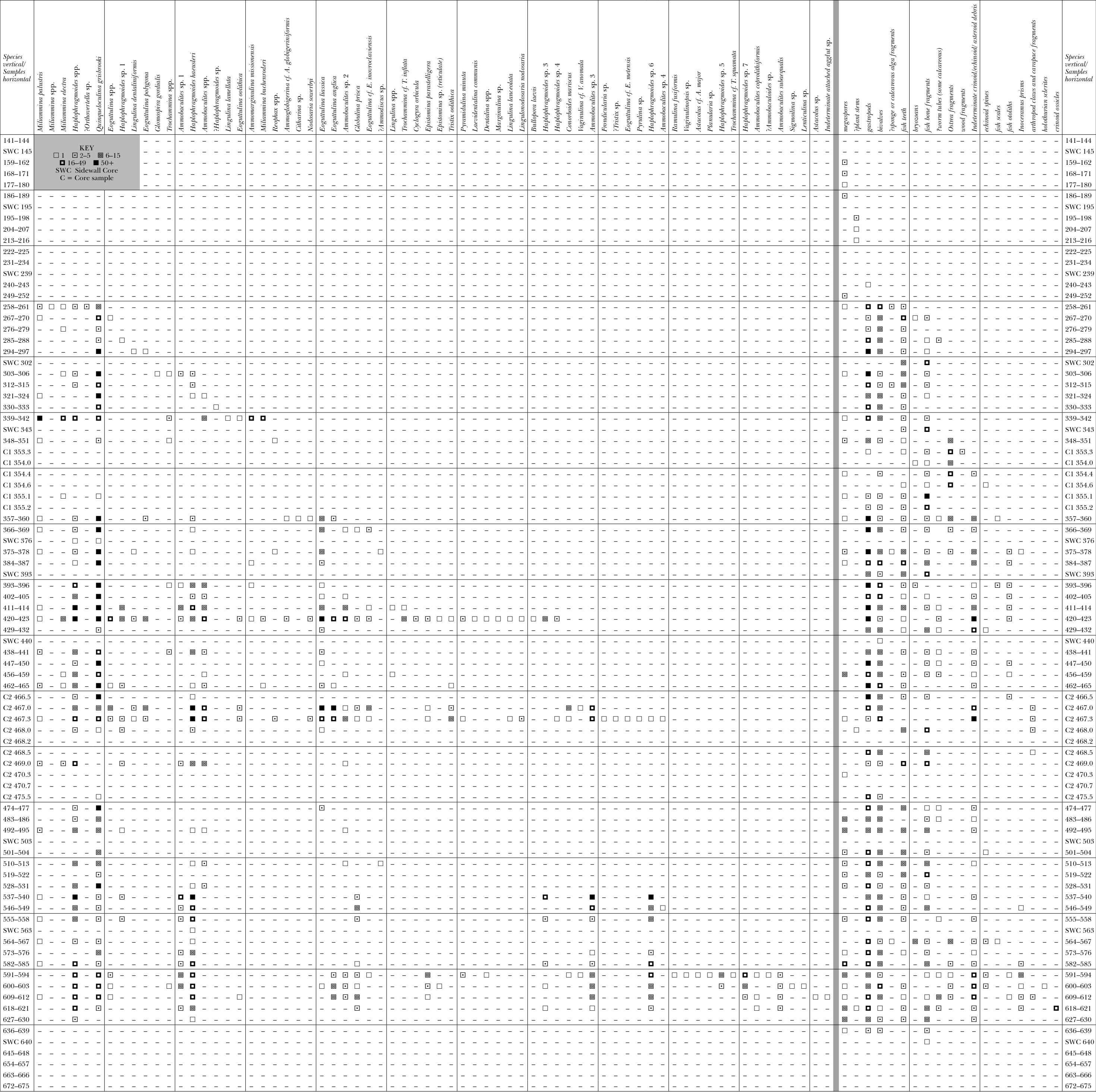


FIGURE 7: FORAMINIFERAL BIOSTRATIGRAPHIC RANGE CHART OF BOREHOLE ST1/71
Depths in metres. No study of miscellaneous microfossils owing to severe cavings in this borehole.

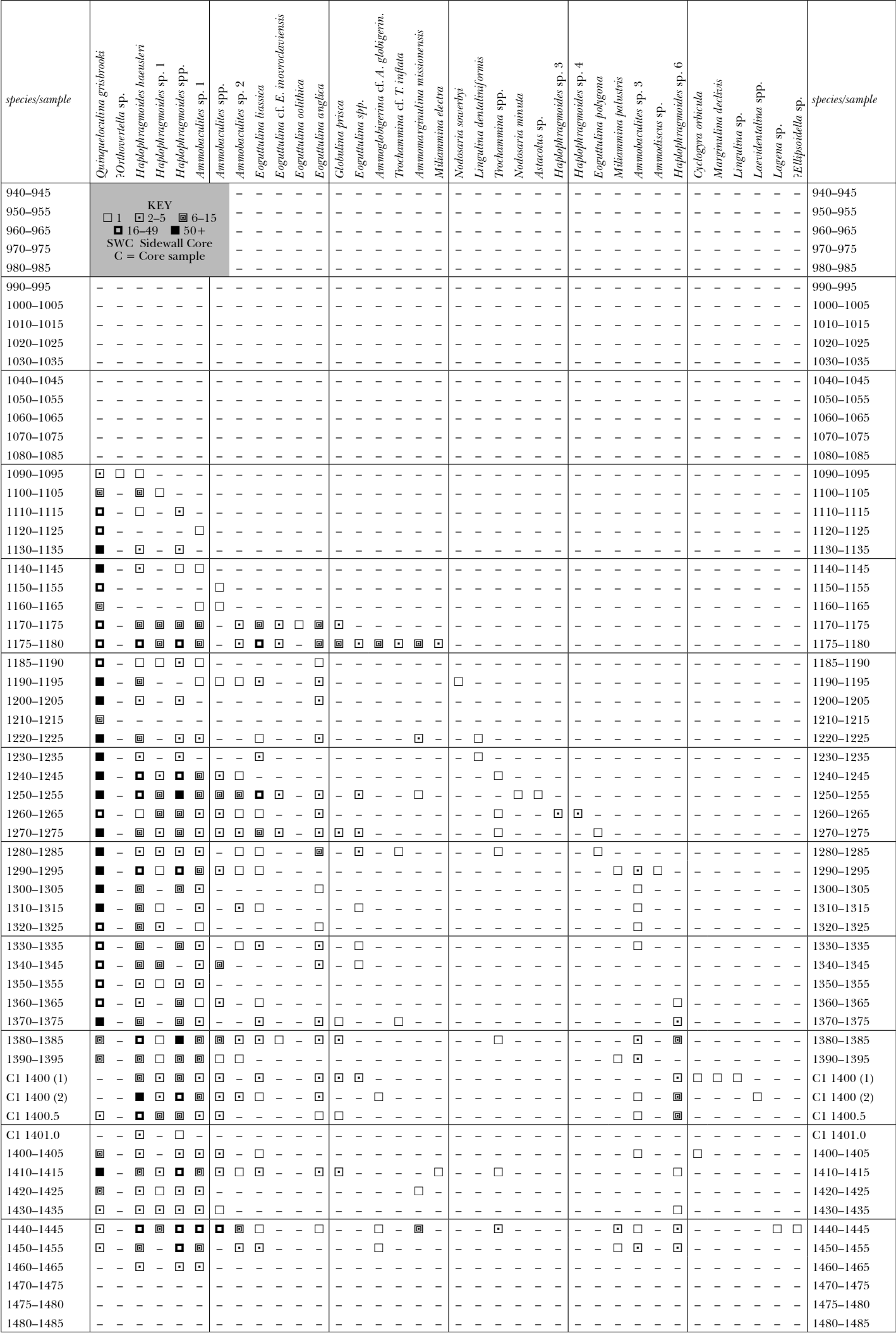


FIGURE 8: FORAMINIFERAL BIOSTRATIGRAPHIC RANGE CHART OF BOREHOLE SW1/08
Sample details given in feet and metres. Borehole originally logged in feet.

